# United States Patent Application for:

## Interface for Controlling a Graphical Image

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# Interface for Controlling a Graphical Image

## CROSS REFERENCE TO RELATED APPLICATIONS

5    This application claims priority from co-pending U.S. Provisional Patent Applications 60/197,656 and 60/197,657, both of which were filed on April 17, 2000 and both of which are incorporated herein by reference in their entireties.

## BACKGROUND

10    The present invention relates to interfacing a user with a computer, such as a computer for performing a virtual reality simulation.

Users interface with electronic and mechanical devices in a variety of
15    applications, and the need for a more natural, easy-to-use, and informative interface is a constant concern. In the context of the present invention, a user interfaces with computer devices for a variety of applications. One such application is interacting with computer-generated environments, such as virtual reality environments, including games, surgical simulations, and application programs. Computer input devices such as mice and trackballs are
20    often used to control a cursor within a graphical environment and provide input in these applications.

In some interface devices, force feedback and/or tactile feedback is also provided to the user, collectively known herein as "haptic feedback." For example, haptic versions of
25    joysticks, mice, gamepads, steering wheels, or other types of devices can output forces to the user based on events or interactions occurring within the graphical environment, such as in a game or other application program. In a virtual reality simulation, it is often desirable to graphically represent a user or a portion of the user in the graphical environment and to allow the user to realistically interact with the graphical environment.

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## SUMMARY

To overcome the deficiencies of the prior art, it is desirable to provide an interface device that improves the interaction of a user with a graphical environment. It is

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further desirable to provide an interface device that applies realistic haptic sensations to a user. In addition, it is desirable to provide an easily implementable and inexpensive interface device.

5     The present invention satisfies these needs. In one aspect of the invention, an interface device for interfacing a user with a computer, the computer running an application program and generating a graphical image and a graphical object, comprises a user manipulatable object in communication with the computer, a sensor to detect a manipulation of the object, the sensor providing a signal to the computer to control the graphical image, and an actuator adapted to provide a haptic sensation to the palm of the user in relation to an interaction

10    between the graphical image and the graphical object, the actuator comprising a member that is deformable to provide the haptic sensation.

In another aspect of the invention, an actuator for providing a haptic sensation to a user interfacing with a computer running an application program comprises a deformable

15    member having a first end, a second end, and an intermediate portion, and a tendon capable of displacing the first end relative to the second end in response to the computer to cause the intermediate portion to contact the user and thereby provide a haptic sensation to the user.

In another aspect of the invention, a mouse for interfacing a user with a computer

20    generating a graphical environment comprising a graphical hand comprises a housing, a position detector to detect a position of the mouse, the position detector capable of providing a first position signal to the computer to control the position of the graphical hand in the graphical environment, and a finger position detector to detect a position of a finger of the user, the finger position detector capable of providing a second position signal to the computer to control a

25    graphical finger on the graphical hand in relation to the position of the finger of the user.

In another aspect of the invention, a mouse for interfacing a user with a computer comprises a housing, a position detector to detect a position of the mouse, a member adapted to contact a finger of the user, the member being capable of being moved by the finger in two

30    directions, and a member position detector to detect a position of the member.

In another aspect of the invention, a method for interfacing a user with a computer running an application program, the computer generating a graphical environment comprising a graphical hand, comprises providing a mouse in communication with the

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computer, detecting a position of the mouse, controlling the position of the graphical hand in relation to the detected position of the mouse, and controlling a shape of the graphical hand in relation to an amount of manipulation of the mouse.

## DRAWINGS

These features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings which illustrate exemplary features of the invention. However, it is to be understood that each of the features can be used in the invention in general, not merely in the context of the particular drawings, and the invention includes any combination of these features, where:

Figure 1 is a schematic diagram of a simulation system according to the present invention;

Figure 2 is a schematic diagram of a simulation system comprising an instrumented glove according to the invention;

Figure 3 is a schematic diagram of a simulation system comprising an instrumented glove with joint angle sensors according to the invention;

Figures 4A through 4C are a schematic side views of the actuation of a palm forcing mechanism according to the invention;

Figures 5A and 5B are schematic exploded and assembled views, respectively, of a version of a palm forcing mechanism according to the invention;

Figures 6A through 6H are schematic side views of embodiments of palm forcing mechanisms according to the invention;

Figures 7A though 7D are schematic side views of embodiments of palm forcing mechanisms including cams according to the invention;

Figure 8 is a schematic sectional side view of an embodiment of a palm forcing mechanism including an inflatable air bladder;

Figure 9 is a schematic sectional side view of an embodiment of a palm forcing mechanism with multiple contacting points;

Figure 10 is a schematic sectional side view of an embodiment of a forcing mechanism according to the invention applying a force to a portion of the body other than the palm;

Figure 11 is a schematic side view of a haptic interface device comprising a palm forcing mechanism and a finger forcing mechanism;

Figure 12 is a schematic perspective view of a finger sensing mouse;

Figure 13 is a schematic sectional side view of a version of a tactile finger sensing mouse;

Figure 14 is a schematic sectional side view of another version of a tactile finger sensing mouse;

Figure 15 is a schematic block diagram of a simulation system comprising a tactile mouse;

Figure 16 is a schematic perspective view of a version of a force feedback finger sensing mouse;

Figures 17A through 17C are schematic perspective views of the forcing mechanism of the version of a force feedback finger sensing mouse of Figure 16;

Figure 18 is a schematic block diagram of a simulation system comprising a force feedback finger sensing mouse;

Figures 19A through 19C are schematic sectional side views of finger sensing mechanisms usable with a mouse device;

Figure 20A is a schematic sectional side view of a finger sensing mechanism

5    comprising a finger receiving extension;

Figure 20B is a schematic view along B-B of the finger receiving extension of Figure 20A;

10   Figure 21 is a schematic sectional side view of another version of a finger sensing mechanism usable with a mouse device;

Figure 22 is a schematic sectional side view of another version of a finger sensing mechanism usable with a mouse device;

15   Figures 23A and 23B are schematic side views of a finger sensing button comprising multiple portions;

Figure 24 is a schematic perspective view of a three dimensional finger sensing

20   mouse; and

Figures 25A through 25C are schematic views of alternative designs for a mouse device.

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## DESCRIPTION

The present invention relates to virtual reality simulations and more particularly to computer simulations involving the control of a graphical image, such as a graphical image

30   that is a graphical representation of a hand or a portion of a hand. Although the process is illustrated at least partly in the context of controlling a graphical hand, the present invention can be used in other simulation and computer interactive processes and/or to control other graphical images and should not be limited to the examples provided herein.

Figure 1 is a schematic illustration of a simulation system **100** according to the invention. The simulation system **100** is capable of generting a virtual reality environment. A display **105** provides a graphical environment **110** to a user. Within the graphical environment **110** is a graphical image **115**. The graphical image **115** may be, for example, a cursor or other

5      graphical object, the position, movement, and/or shape of which is controllable. For example, the graphical image **115** may be a pointer cursor, a character in a game, a surgical instrument, a view from the end of a surgical instrument, a representative portion of the user, or the like. Also within the graphical environment is a graphical object **120** such as a ball, as shown, or any other graphical representation including another graphical image that may be controlled by the user or

10     by another user. A controller **125** in communication with the display **105** is capable of generating and/or controlling the graphical environment **110**, for example by executing program code including an application program related to the simulation. A user object **130** is manipulatable by a user, and the manipulation of the user object **130** controls the position, orientation, shape and/or other characteristic of the graphical image **115** within the graphical

15     environment **110**, for example by directly correlating a position of the user object **130** with a displayed position of the graphical image **115** or by correlating a position of the user object **130** with a rate of movement of the graphical image **115**. Either the entire user object **130** may be manipulatable by the user or a portion of the user object **130** may be manipulatable relative to another portion of the user object **130**. For example, the user object may be a surface that is

20     engaged by one or more hands of a user, such as a joystick, a mouse, a mouse housing, a stylus, a knob, an elongated rigid or flexible member, an instrumented glove, or the like and may be moveable in from one to six degrees of freedom.

Optionally, haptic feedback may be provided to the user to increase the realism

25     of the virtual reality environment. For example, when a predetermined event occurs within the graphical environment **110**, such as an interaction of the graphical image **115** with the graphical object **120**, the controller **125** may cause an actuator **135** to output a haptic sensation to the user. In the version shown, the actuator **135** outputs the haptic sensation to the user object **130** through which the sensation is provided to the user. The actuator **135** and the user object **130**

30     may be part of a haptic interface device **140**. The actuator **135** may be positioned in the haptic interface device **140** to apply a force to the user object **130** or to a portion of the user object. For example, the haptic interface device **140** may comprise a user object **130**, such as a mouse housing, having an actuator **135** within the user object **130**, such as a vibrating motor within the mouse housing, or the haptic interface device may comprise a user object **130**, such as a mouse,

that is mechanically linked to an actuator **135**. Alternatively, the actuator **135** and the user object **130** may be separate structures, and the actuator **135** may provide a haptic sensation directly to the user, as shown by the phantom arrow in Figure 1.

5         The actuator **135** may provide the haptic sensation actively or passively. For example, the actuator **135** may comprise one or more motors coupled to the user object **130** to apply a force to the user or to the user object **130** in one or more degrees of freedom. Alternatively or additionally, the actuator **135** may comprise one or more braking mechanisms coupled to the user object to inhibit movement of the user or the user object **130** in one or more

10    degrees of freedom. By haptic sensation it is meant any sensation provided to the user that is related to the user's sense of touch. For example, the haptic sensation may comprise kinesthetic force feedback and/or tactile feedback. By kinesthetic force feedback it is meant any active or passive force applied to the user to simulate a force that would be experienced in the graphical environment **110**, such as a grounded force applied to the user or the user object **130** to simulate

15    a force experienced by at least a portion of the graphical image **115**. For example, if the graphical image **115** is positioned against a surface, a barrier or an obstruction, the actuator **135** may output a force against the user object **130** preventing or retarding movement of the user or the user object **130** in the direction of the barrier or obstruction. By tactile feedback it is meant any active or passive force applied to the user to provide the user with a tactile indication of a

20    predetermined occurrence within the graphical environment **110**. For example, a vibration, click, pop, or the like may be output to the user when the graphical image **115** interacts with a graphical object **120**. Additionally, tactile feedback may comprise a tactile sensation applied to approximate or give the illusion of a kinesthetic force. For example, by varying the frequency and/or the amplitude of an applied vibration, variations in surface textures of different graphical

25    objects can be simulated or by providing a series of clicks when a graphical image penetrates an object, resistance to the penetration can be simulated. For example, in one version a kinesthetic force sensation, such as a spring force, may be applied to the user whenever the graphical image **115** engages the graphical object **120** to simulate a selectively deformable surface. Alternatively or additionally, a tactile sensation, such as a pop, may be applied to the user when

30    the graphical image **115** is moved across a surface of the graphical object **120** to simulate a texture of the graphical object **120**.

The controller **125** may be a computer **150**, or the like, such as the computer shown in Figure 2. In one version, the computer **150** may comprise a processor and may be

able to execute program code. For example, the computer may be a personal computer or workstation, such as a PC compatible computer or Macintosh personal computer, or a Sun or Silicon Graphics workstation. The computer 150 may be operable under the Windows™, MacOS, Unix, or MS-DOS operating system or similar. Alternatively, the computer 150 can be

5      one of a variety of home video game console systems commonly connected to a television set or other display, such as systems available from Nintendo, Sega, or Sony. In other embodiments, the computer 150 can be a "set top box" which can be used, for example, to provide interactive television functions to users, or a "network-" or "internet-computer" which allows users to interact with a local or global network using standard connections and protocols such as used

10     for the Internet and World Wide Web. The computer 150 may include a host microprocessor, random access memory (RAM), read only memory (ROM), input/output (I/O) circuitry, and/or other components of computers well-known to those skilled in the art. The computer 150 may implement an application program with which a user is interacting via peripherals, such as haptic interface device 140 and/or user object 130. For example, the application program can be

15     a simulation program, such as an interactive digital mockup of a designed feature, a medical procedure simulation program, a game, etc. Specifically, the application program may be a computer aided design or other graphic design program, an operating system, a video game, a word processor or spreadsheet, a Web page or browser that implements, for example, HTML or VRML instructions, a scientific analysis program, or other application program that may or may

20     not utilize haptic feedback. Herein, for simplicity, operating systems such as Windows™, MS-DOS, MacOS, Linux, Be, etc. are also referred to as "application programs." The application program may comprise an interactive graphical environment, such as a graphical user interface (GUI) to allow the user to input information to the program. Typically, the application provides images to be displayed on a display screen 155 and/or outputs other feedback, such as auditory

25     signals. The computer 150 is capable of generating a graphical environment 110, which can be a graphical user interface, game, simulation, such as those described above, or other visual environment. The computer 150 displays graphical objects 120, such as graphical representations and graphical images, or "computer objects," which are not physical objects, but are logical software unit collections of data and/or procedures that may be displayed as images

30     by the computer on display screen 155, as is well known to those skilled in the art. The application program checks for input signals received from the electronics and sensors of the user object 130, and outputs force values and/or commands to be converted into haptic output for the actuator 135. Suitable software drivers which interface such simulation software with computer input/output (I/O) devices are available from Immersion Corporation of San Jose,

California. Display screen **155** can be included in the computer and can be a standard display screen (LCD, CRT, flat panel, etc.), 3-D goggles, or any other visual output device.

In one version of the simulation system **100**, the user object **130** comprises an instrumented glove **160**. Within or on the instrumented glove **160** are one or more sensors that are capable of detecting a manipulation of the glove. A signal indicative of the detected manipulation is provided to the computer **150**, optionally through glove sensor interface **165**, to control the position, orientation, and/or shape of the graphical image **115**, which may be for example a graphical hand **170** as shown in the version of Figure 2.

The position of the instrumented glove **160** may be used to control the position of the graphical hand **170** in the graphical environment **110**. The position of the instrumented glove **160** may be detected by one or more position sensors adapted to detect the position of the instrumented glove **160** in one, two, or three dimensions. The position sensor may include a grounded link connected to the instrumented glove **160**. Alternatively, the position sensor may detect the position of the instrumented glove **160** in space, without being physically connected to a reference. For example in one version, the instrumented glove **160** comprises a Polhemus™ or Ascension™ electromagnetic position sensor to detect the three dimensional position of the instrumented glove **160** in space. The position sensor generates a signal related to the position of the instrumented glove **160** and the signal is provided to the computer **150**. The computer **150** then controls the display of the graphical hand **170** in proportion to the signal. In one version, the displayed position of the graphical hand **170** is directly related to the position of the instrumented glove **160**.

The orientation of the instrumented glove **160** may alternatively or additionally be used to control the graphical hand **170**. An orientation sensor may be provided to detect the absolute or relative rotation of the instrumented glove **160** about one, two, or three orthogonal axes. As with the position sensor, the orientation sensor may be grounded or may be able to detect rotation in space. A signal related to the orientation of the instrumented glove **160** is then provided to the computer **150** which uses the signal to correspondingly control the display of the graphical hand **170**. Accordingly, the rotation of the instrumented glove **160** about an axis results in a displayed rotation of the graphical hand **170** about an axis, for example a parallel axis. In one version, a single sensor may be used to detect both position and orientation. For example, a Polhemus ™ or Ascension ™ sensor may be used to detect the position of the

instrumented glove **160** in six degrees of freedom. The computer **150** may then use the six degree of freedom signal to control the displayed position and orientation of the graphical hand **170**.

5          Alternatively or additionally, the shape of the graphical hand **170** (or other graphical image **115**) may be controlled by a user manipulating the instrumented glove **160**. For example, one or more joint angle sensors may be provided to sense rotation about a particular joint in the hand (or other body part). The computer **150** may then control the display of the graphical hand **160** in relation to the sensed motion within the hand to, for example, show

10       a corresponding movement of the graphical hand **170**. In this way, the shape of the graphical hand **170** can be controlled to in response to manipulation of the instrumented glove **160** by the user. For example, a simulation may comprise the display of the graphical hand **170** to simulate the movement of the user's hand, such as by showing the graphical hand **170** closing and/or grasping when the user closes his or her hand or makes a grasping motion. One or more joint

15       angle sensors **175** may be positioned to detect the movement of a finger of the user. In another version, the movement of a plurality of fingers may be detected. In a relatively simple version, a single digital or analog sensor detects either an open condition or a closed condition of the user's hand, and the computer **150** correspondingly displays the graphical hand **170** either as being open or as being closed or grasping an object in the graphical environment **110**. In

20       another version, the joint angle position sensor may comprise an analog sensor that provides a variable signal by which the display of the graphical hand **170** may be controlled. The joint angle sensor may comprise one or more of a stain gage, a fiber optic sensor, a potentiometer, or the like.

25       In one version, the instrumented glove **160** may comprise both a position sensor and one or more joint angle sensors. For example, the instrumented glove **160** may comprise a CyberGlove ™ available from Virtual Technologies, Inc. in Palo Alto, California, and described in U.S. Patents 5,047,952 and 5,280,265, both of which are incorporated herein by reference in their entireties. In this version, individual joint angle sensors **175** comprise two long, flexible

30       strain gages mounted back to back. The strain gage assemblies reside in guiding pockets sewn over a particular joint. When the joint is flexed, one of the strain gages of the corresponding pair of gages is in tension, while the other strain gage is in compression. Each pair of two strain gages comprise the two legs of a half bridge of a common Wheatstone bridge configuration. An analog multiplexer is used to select which of the half bridge voltages is to be sampled by an

analog-to-digital converter. The maximum strain experienced by each gage is adjusted by varying the thickness and elastic modulus of the backing to which the gages are mounted. The backing is selected to maximize the signal output without significantly reducing the fatigue life of a gage.

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In use, a user contacts the user object **130** to interact with the graphical environment **110**. In the version shown in Figure 2, the user dons the instrumented glove **160** and moves all or a portion of his or her hand to control the graphical hand **170** which mimics the motion of the user's hand. For example, the user may move his or her hand to the left in order

10   to cause the graphical hand **170** to be rendered so as to appear to touch the graphical object **120**. In additional, the user may slightly close and appropriately move his or her hand to make the graphical hand **170** appear to grasp the graphical object **120**.

The realism of the simulation can be increased by providing an actuator **135**
15   adapted to provide one or more haptic sensations to the user during the user's interaction with the graphical environment **110**. The actuator may either provide the haptic sensation directly to the user or may apply the haptic sensation to the user through the user object, for example by applying a force to the surface of the instrumented glove **160**. This allows the user to not only visualize the graphical hand **170** contacting the graphical object **120**, but also to receive an
20   indication through the user's sense of touch that the object has been contacted, thereby providing a more immersive experience. The actuator **135** may comprise a palm forcing mechanism **180** for providing a haptic sensation to the palm of the hand, as shown in phantom in Figure 2. It has been discovered that by providing a haptic sensation to the palm, the user's perception of realistic interaction with a graphical object **120** is enhanced. For example, a
25   haptic sensation may be provided to the palm in coordination with the graphical hand **160** grasping the graphical object **120** to simulate an actual grasping of an object. Accordingly, in the version of Figure 2, the computer **150** controls the output of a haptic sensation to the user's palm by providing a signal, optionally though actuator interface **185**, to cause the palm forcing mechanism to be actuated.

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The actuator **135** may include the palm forcing mechanism **180**, and optionally may additionally be able to provide a haptic sensation to other portions of the user and may include additional actuators. In one version, the haptic sensation is delivered essentially only to the palm. It has been discovered that during some simulations, such as a power grasping

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simulation, a haptic sensation in the palm is perceived by the user as a realistic sensation. Accordingly, by providing an actuator that delivers a haptic sensation to the palm, realistic haptic feedback for many simulations may be provided in an easily implementable and inexpensive version. In other versions, the palm haptic sensations may be combined with haptic

5 sensations delivered to other portions of the user, as will be described below.

Figure 3 shows how the electrical and mechanical signals propagate through an embodiment of the simulation system **100**. In this version, an actuating mechanism, such as a DC servo motor causes the palm forcing mechanism **180** to apply a force to the palm. The

10 computer **150**, or other controller or signal processor, sends a digital value representing the desired actuation level control signal to the digital-to-analog converter **190**. The analog output of the digital-to-analog converter **190** may then be amplified by a variable gain amplifier **195** to produce an analog voltage activation signal. This voltage is placed across the servo motor, driving the motor a desired amount. The voltage signal may alternately be converted to a

15 current activation signal for driving the motor at a desired torque. The joint angle sensors **175** generate an analog signal related to the relative angle of rotation of a joint. The signals from the joint angle sensors **175** are passed through an analog-to-digital converter **200** to provide digitized values to the computer as a physical state signal. In the graphical environment **110**, the physical state signal may then cause motion in a corresponding graphical hand **170**. If the

20 graphical hand **170** or a portion of the graphical hand **170** contacts a graphical object **120** in a predetermined manner, a haptic sensation is output to the palm of the user. For example, in one version, the computer **150** calculates the force to be applied to the palm using data related to the graphical object's shape and/or compliance. The computer **150** then causes an activation signal to be sent to the palm forcing mechanism to convey haptic information about that virtual force.

25 The computer **150**, digital-to-analog converter **190**, analog-to-digital converter **200**, bus **205** and variable gain amplifier **195** may be elements of a signal processor.

The palm forcing mechanism **180** may be designed to be comfortably positionable in or near the palm of the user. The palm forcing mechanism **180** may be

30 incorporated into the user object **130** or may be a separate mechanism. For example, in one version, the palm forcing mechanism **180** is an independent unit that is adapted to contact the palm of a user. The palm forcing mechanism **180** may either directly contact the palm of the user or may contact the palm through at least a portion of the user object **130**. For example, when used with an instrumented glove **160**, the palm forcing mechanism **180** may be positioned

on the outside of the instrumented glove **160**. The palm forcing mechanism **180** may be held in place by a strap that extends around the hand or it may be otherwise attached to the hand, such as by adhesive tape. Alternatively, the palm forcing mechanism **180** may be positioned within the instrumented glove **160**. In addition, the palm forcing unit may include a rigid plate secured

5 to the hand that serves as a grounding member against which the palm forcing mechanism **180** can exert a force. In another version, the palm forcing mechanism **180** may be grounded and the user may place his or her hand on or in proximity to the palm forcing mechanism **180** during use.

10 A version of a palm forcing mechanism **180** is shown in Figure 4A. A user's hand **210** is shown in a cross-section taken along section A-A of Figure 3 (thumb not shown), and a palm forcing mechanism **180** is positioned within or near the palm **215** of the user. The palm forcing mechanism **180** comprises a force applying member **220** including a surface **225** that is adapted to contact and/or exert a force against the palm **215** when actuated. In this

15 version, the force applying member **220** comprises a deformable member **230**, such as strip of metal, sufficiently stiff to retain a slightly bowed shape, as shown in Figure 4A. A first end **235** of the deformable member **230** is fixed, for example by being fixed against translation relative to a guide member **240**. A second end **245** of the deformable member **230** is connected to a distal end of a tendon **250** which is slidably disposed within the guide member **240**. The tendon

20 **250** extends through the guide member **240** and is connected at its proximal end to an actuating mechanism **255**. The actuating mechanism **255** is able to exert a pulling force on the tendon **250**, that is it is able to exert a force in the direction shown by arrow **260**. When the actuating mechanism **250** pulls on the tendon **250**, a force is applied to the second end **245** of the deformable member **230** causing the second end **245** to be brought nearer the first end **235**,

25 thereby further bowing the deformable member **230**.

As more force is applied, the deformable member **230** contacts the palm **215**, and the user experiences a contact sensation, as shown in Figure 4B. Thus, when the actuating mechanism **255** is controlled by the computer **150**, the application of the contact sensation may

30 be coordinated with a contact event in an ongoing simulation. As a graphical hand **170**, for example, grasps a graphical object **120**, the user may simultaneously visualize the grasp and feel the sensation in his or her palm by actuation of the palm forcing mechanism **180**. Optionally, the actuating mechanism **255** may be capable of continuing to exert a pulling force on the tendon **250**, as shown in Figure 4C, to apply a stronger force on the palm **215**. In this way, the

simulation system **100** may be able to provide a contact sensation related to the strength of the user's grasping of the graphical object **120** or to simulate a weight or inertia of the graphical object **120**.

5             In one version, the deformable member **230** may comprise a leaf spring that is biased into a configuration substantially as shown Figure 4A. In this version, the tendon **250** may be a flexible cable or wire, sufficiently rigid in tension to transmit the pulling force from the actuating mechanism **255** to the second end **245** of the deformable member **230** but sufficiently flexible to pass from the first end **235** to the actuating mechanism **255** along a non-

10   linear path. For example, the tendon **250** may comprise Dacron™ or Kevlar™ slidably disposed in one or more fixed tubular casings, as described in U.S. Patent 5,631,861 which is incorporated herein by reference in its entirety. Alternatively, the tendon **250** may comprise metallic material or may be a composite. The bias of the leaf spring is used to return the deformable member **230** to a non-contacting position when the pulling force is removed by the

15   actuating member **255**. This simplifies the control process associated with applying a contact sensation. For example, the computer **150** may provide a "pull" signal to drive the actuating mechanism **255** when a contact sensation is desired, and may remove the "pull" signal, resulting in no driving of the actuating mechanism **255** when there is no contact sensation desired, the bias of the spring acting as an active member returning the palm forcing mechanism

20   **180** to the condition of Figure 4A. In an alternative version, the tendon **250** may be rigid in both tension and compression and the actuating mechanism **255** may drive the tendon **250** in both directions to controllably bow or unbow the deformable member **230**.

            Figures 5A and 5B show exploded and assembled views, respectively, of a

25   version of a palm forcing mechanism **180** comprising a biased deformable member **230** and a flexible tendon **250**. This version includes a housing **265** which serves to fix the first end **235** of the deformable member **230** to the guide member **240**. The housing includes a top surface **270** which is shaped to be positionable adjacent the palm **215** of a user. The top surface **270** may either be spaced from the palm **215** or may rest against the palm **215**. It has been

30   discovered that the continuous contact of the top surface **270** against the palm **215** does not affect the user's perception of a contact sensation. The housing **265** may be made of rigid metal, plastic, and/or ceramic material. The housing **265** includes openings **275** in a side wall for receiving prongs **280** extending from the first end **235** of the deformable member **230**. The openings **275** include walls **277** that abut against the prongs **280** to limit translation of the

deformable member **230** and to allow the deformable member **230** to bow. The prongs **280** may be rotatable within the openings **275** to facilitate the bowing. A connecting member **285** connects the second end **245** of the deformable member **230** to the tendon **250**. The connecting member **285** comprises eyelets **290** which are received around extending prongs **295** of the

5 second end **245**. The prongs **295** also extend into longitudinally extending slots **300** in the housing **265**. Another eyelet **305** is connected to the end of the tendon **250** by suitable means, such as by gluing, soldering, or wrapping the tendon around the eyelet **305**. Accordingly, as the tendon **250** is pulled, the connecting member **285** pulls on the prongs **295** which then slide within slot **300**. This action causes the deformable member **230** to bow, as discussed above.

10 When the bowing is sufficient to cause the surface **225** of the deformable member **230** to extend above the top surface **270** of the housing **265**, a contact sensation is applied to the palm **215**.

Another version of the palm forcing mechanism **180** is shown in Figure 6A. In this version, the deformable member **230** comprises a pivoted member comprising a first bar **310** and a second bar **315** pivotally connected at a hinge **320**. The second bar **315** is also

15 pivotally connected to the guide member **240**, or to a housing, for example at a second hinge **325**. The tendon **250** is attached to the first bar **310**, and as the tendon **250** is pulled, the hinge **320** is forced upwardly and it or another portion of the deformable member **230** contacts the palm **215**. In another version, a strap or the like (not shown) and/or a rigid plate is positioned

20 below the distal end of the first bar **310** to inhibit the distal end from being pulled downwardly, thereby increasing the force applied to the palm **215** by the deformable member **230**. Alternatively or additionally, a housing similar to the one shown in Figures 5A and 5B may provide a base against which the deformable member **230** may be forced toward the palm **215**.

25 Figure 6B shows another version of a palm forcing mechanism **180**. This version is shown with a deformable strip **340**, similar to the leaf spring discussed above, as the deformable member **230** but may be used with pivotally connected bars, such as those shown in Figure 6A. The version of Figure 6B includes a motor **350** receiving a rotatably driven shaft **355**. The shaft **355** includes interior threads that engage threads on a rod **345** that is connected

30 to an end **347** of the deformable strip **340**. As the motor **350** rotates shaft **355** in a first direction, the rod **345** is retracted into the shaft **355** and the end **347** of the deformable strip **340** is moved toward the motor **350**. The motor **350** is non-rotatably fixed to the other end **348** of the deformable strip **340**, for example by rigid member **360**. Accordingly, movement of the first end **347** toward the motor results in movement of the first end **347** toward the second end

348 and a corresponding bowing of the deformable strip 340. As shown the motor 350 is positioned within the palm forcing mechanism 180. Alternatively, the motor 350 may be located remotely, and the rod 345 may pass through a lumen in the rigid member 360, for example. The actuating mechanism 255 may alternatively be a solenoid or voice coil, or the like.

Figure 6C shows a version of the palm forcing mechanism 180 similar to the version shown in Figure 4A. However, in the version of Figure 6C, the actuating mechanism 255 is positioned on the hand of the user, for example by being fixed to the backside of the hand, as shown. This version is advantageous in that the tendon 250 may be contained within the haptic interface device 140 reducing the likelihood of entanglement of the tendon 250 with wires or cables that may be present. Figure 6C also shows a version of the actuating mechanism comprising a motor 365 which rotatably drives a pulley 370 on which is wound the tendon 250.

Figure 6D shows a version of the palm forcing mechanism 180 where a contact sensation is applied to the palm by pushing on the tendon 250 rather than by pulling on the tendon 250. In this version, the tendon 250 may be sufficiently rigid in compression to adequately apply a force to the palm forcing mechanism 180. In this version, the deformable member 230 is inverted and includes a contact member 380 on its inner surface. The contact member 380 includes a surface 385 adapted to engage the palm 215 when the palm forcing mechanism 180 is actuated. To actuate the palm forcing mechanism 180 the tendon 250 is pushed toward the second end 245 of the deformable member 230 as shown by arrow 387. This forces the second end 245 away from the first end 235 and straightens the deformable member 230 thereby forcing the contact member 380 upward and against the palm 215. An opening 390 may be provided within the contact member 380 to allow the tendon 250 to pass therethrough in all operative positions of the contact member 380. Alternatively, the version of Figure 6D can be used with a flexible tendon 250. In this version, a the deformable member may be biased so that the ends are biased apart. Tension applied to the tendon 250 overcomes the bias and release of the tension actuates a contact sensation.

Figure 6E shows a self-contained version of the palm forcing mechanism 180 with an interior actuating mechanism 255. The actuating mechanism 255 is on a lower member 395 which is held in place by a housing and/or a strap. The actuating member 255 drives a piston 400 upwardly and against the deformable member 230 to force the deformable member

against the palm **215**.  Alternatively, the members may be separated from one another and the actuating mechanism **255** may displace the two members to contact the palm **255**.  The actuating mechanism may be a solenoid or voice coil actuator or may comprise a rotating threaded shaft that receives a rod attached to the deformable member, as discussed above.

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In one version of the palm forcing mechanism **180**, the tendon **250** may be used to directly apply the force to the palm **215**.  For example, the guide member **240**, a version of which is shown in cross-section in Figure 6F, may comprise a channel **405** that is shaped to direct the tendon **250** toward the palm **215**.  Optionally, the distal end of the tendon **250** may

10 include a force transmitting cap **410** to distribute the force to applied to the palm **215**.  As a force is applied in the direction of arrow **415**, the tendon contacts the palm **215**.  The cap **410** may include an extension **420** that prevents the cap **410** and the tendon **250** from being retracted into the channel **405**.

15 Figure 6G shows another version of the palm forcing mechanism **180**.  In this version, a plate **430** is position below the palm **215**.  The plate includes a contacting portion **435** extending toward the palm **215**.  The tendon **250** is connected to the plate **430** at an end near the guide member **240**.  By pulling on the tendon **250** the plate **430** is moved toward the palm **215** and the contacting member **435** applies a force to the palm **215**.  Figure 6G shows the

20 actuating mechanism **255** on the backside of the hand.  Alternatively, a remote actuating mechanism may be used.

Figure 6H shows a strap **440** that may be used to secure any of the disclosed palm forcing mechanisms **180** or portions thereof to the hand **210**.  The strap **440** may extend

25 around the hand and may have ends that are attachable to one another.  For example, as shown, the strap ends are attached by a hook and loop type fastener **450**.  Other suitable attachments may also be used.  Alternatively, the ends may be separately fastened to the hand, such as by adhesive, or may be fastened to a plate or the like on the back of the hand **210**.  The strap **440** may include one or more openings through which elements, such as the tendon **250**, the guide

30 member **240**, or electronic components, may pass.

The actuator **135** may be designed to reduce its operating space.  For example, when applying a force to the palm **215**, or to other portions of the body, it may be undesirable to have the force receiving portion of the body burdened with a large actuator **130** that hinders the

movement of the user or reduces the realism of the simulation.  In one version of the ivention, the space requirements of the actuator **135** may be reduced by a mechanism that allows the force applied to the user to be in a different direction than the actuated force.  For example, in the embodiments of Figures 4A-4C, 5A-5B, 6A-6D, and 6G, the actuators **135** reduce their footprints by providing a force to the user in a direction substantially orthogonal to the direction of the application of an actuating force.  This application of a substantially orthogonal force is advantageous in that the space occupied by the actuator **130** may be reduced allowing for the actuating mechanism **255** to be, for example, remotely located and allowing for the tendon **250** to be less obstructively directed away from the portion of the body to which the force is being applied.  The other embodiments may also be designed to reduce the amount of position of space they occupy.

In another version of an actuator **135** that allows for the application of an actuating force in a direction different than, and optionally substantially orthogonal to, the direction of an applied force to the user, a tendon **250** may be used to initiate a cam action that applies a force to the user.  Examples of cams are shown in Figures 7A though 7D.  In the version of Figure 7A, the palm forcing mechanism **180** comprises a lower member **460** and an upper member **465** which includes a surface **470** adapted to apply a force to the palm **215**.  Pivotally and eccentrically attached to the lower member **460** is a cam **475**.  The tendon **250** is attached to the cam **475** so that a force on the tendon **250** in the direction of arrow **480** causes the cam **475** to rotate and separate the lower member **460** from the upper member **465**.  Since the lower member **460** is grounded, for example by strap **440**, the upper member **465** is forced upwardly and the surface **470** applies a contact sensation to the palm **215**.  A linear cam is shown in the version of Figure 7B.  The tendon **250** is connected to a block than includes a cam surface **500**.  Above the block **485** is a force applying member **490** that has a lower cam surface **500** and an upper surface **495** for contacting the palm **215**.  When the block **485** is pulled by the tendon **250** the cam surfaces **500** cause the force applying member **490** to move upwardly and contact the palm **215**.  the guide member **240** may include an extension **510** to guide the movement of the force applying member **490**.  In the version of Figure 7C, the lower member **460** comprises a threaded rod **515**.  A nut **520** having internal threads is received on the rod **515**.  The tendon **250** is attached to the outer surface of the nut **520** so that a force in the direction of the arrow **480** causes the nut to rotate about the rod axis, thereby moving the nut **520** upward and applying a force to the palm **215**.  The force may be applied by a surface **525** on the nut, or an upper member may be attached to the nut **520**.  Alternatively, the rod and nut may be

replaced by a telescoping arrangement **530** where rotation of a pulley **535** results in extension of telescoping members, as shown in Figure 7D. Alternatively, a turn-buckle type arrangement may be used.

5         Figure 8 shows a pneumatic version of the palm forcing mechanism **180**. An inflatable air bladder **540** is positioned under the palm **215**. A pump **545** or other source of pressurized air is connected to the air bladder **540** by way of a controllable valve **550**. In one version, the computer **150** controls the opening and closing of the valve **550** to selectively allow for inflation of the air bladder **540**. Alternatively, the computer **150** may control the operation 10   of the pump **545**. In one version, the air bladder **540** may include a spring mechanism that biases the air bladder **540** into the deflated position shown in Figure 8 and the valve **550** may be a one-way valve when in the closed condition so that the force on the palm **215** may be removed when the valve is closed. In another version, one or more openings may be provided in the bladder **540** that allow the escape of air. When the valve is open the volumetric flow rate of the 15   inflow of fluid may be greater than the volumetric flow rate of the escape of fluid to achieve a desired inflation of the air bladder **540**.

        Any of the above palm forcing mechanism **180** may be modified to apply multipoint contact of the palm **215**. For example, Figure 9 shows a version of the palm forcing 20   mechanism **180** where the deformable member **230** comprises a first portion **555** and a second portion **560** that contact the palm **215** at different locations when the tendon **250** is pulled a sufficient amount. Optionally, the tendon **250** may pass through openings **565** in the portions to increase the stability of the deformable member **230**. The multi-point contacting ability can provide a realistic contact sensation to the user when the graphical object **120** to be grasped has 25   a non-continuous surface. In a more advanced version, the two portions may be separately actuated by two separate tendons. This allows for multiple points to be independently contacted by the palm forcing mechanism **180**.

        The palm forcing mechanism **180** may be used to apply a tactile sensation, such 30   as a vibration, to the palm. For example, in the version shown in Figure 4A, the actuating mechanism **255** may apply an oscillating or cyclical pulling force on the tendon **250** to vibrate the palm. In one version the force applying member **220** may cyclically contact the palm **215**. In another version, the force applying member **220** may be in continuous contact with the palm **215** and the haptic information may be provided through the tactile sensations where the

magnitude of the force applied to the palm is varied. Any of the above disclosed embodiments may be vibrated in this manner. Additionally, the palm forcing mechanism **180** may comprises a rotating eccentric mass, as described in U.S. Patent 6,088,017 which is incorporated herein by reference in its entirety.

5          The actuating mechanism **255** may comprise a servo motor, solenoid, or voice coil as described above or may comprise other actuators known in the art, such as piezoelectric, shape memory alloy, pneumatic, hydraulic, and vapor pressure actuators. Other known electrical, electromagnetic, electromechanical or the like actuators may alternatively or

10       additionally be used.

          Any of the above described forcing mechanisms may be adapted to apply a force to a portion of a user's body other than the palm. For example, as shown in Figure 10, a force applying member **220** may comprise a deformable member **230** actuated by a tendon **250** to

15       apply a haptic sensation to the tip of a finger. A low profile version of the mechanism may be worn under or over an instrumented glove **160** to provide realistic haptic sensations to the user's finger.

          The palm forcing mechanism **180** may be used in coordination with other forcing mechanisms. For example, the palm forcing mechanism **180** may be used with a device capable

20       of provide haptic feedback to one or more fingers, as shown in Figure 11. In this version, the haptic interface **140** comprises a finger forcing mechanism **570** and the palm forcing mechanism **180**. The finger forcing mechanism **570** may comprise a tip portion **575** adapted to contact a portion of a user's finger. The tip portion **575** is connected to a tendon **250'**. Tendon **250'** may

25       be pulled by an actuating mechanism (not shown) to exert a force on the finger. A force-augmenting structure **580** may also be provided to provide more realistic forces to the finger tip. In one particular version, the palm forcing mechanism **180** is used in conjunction with a CyberGrasp™ device available from Virtual Technologies, Inc. and described in U.S. Patents 5,631,861 and 6,042,555, both of which are incorporated herein by reference in their entireties.

30       The finger forcing mechanism **570** is worn on the hand and applies computer-controlled force feedback to one or more, preferably each, of the fingers. The haptic interface **140** may be advantageously used to simulate the interaction of the graphical hand **170** and a graphical object **120**. An instrumented glove **160** is worn to control the graphical hand **170**. The user uses his or her hand to grasp the graphical object **120** with the graphical hand **170**. The computer transmits

force commands to the actuating mechanisms associated with the finger forcing mechanism **570** so the user may "feel" the graphical object **120** in his or her fingertips. The computer also transmits force commands to the palm forcing mechanism **180** so that the user may also "feel" the graphical object **120** in his or her palm. Thus, both precision grasps, which primarily use the finger tips, and power grasps, where an object is held against a user's palm, may be simulated. The palm forcing mechanism **180** in this version may be held in place by strap **440** which extends around the hand and is attached to a palm plate used to secure the finger forcing mechanism **570** to the hand. In one version, the palm forcing mechanism **180** and the finger forcing mechanism **570** may use the same force generating and force transmitting system, for example one or more DC motors with spools for respectively winding the tendon **250** and the tendon **250'**. The more electrical current that is send to the motors, the more torque is applied to the spools to force the tendons **250, 250'**. In another version, the palm forcing mechanism **180** may be used with the CyberTouch™ device available from Virtual Technologies, Inc., and described in U.S. Patent 6,088,017 which is incorporated herein by reference in its entirety. Additionally or alternatively, the palm sensing mechanism **180** may be used with the CyberForce™ device available from Virtual Technologies, Inc. and described in U.S. Patents 5,631,861 and 6,042,555 and in U.S. Provisional Patent Application 60/191,047 filed on March 21, 2000, all of which are incorporated herein by reference in their entireties. In this version, the haptic interface **140** comprises a finger forcing mechanism **570**, a palm forcing mechanism **180** and a grounded force applying member attachable to the user at the wrist, for example. The grounded force applying member may be capable of applying forces in from one to six degrees of freedom and may also be capable of detecting movement in from one to six degrees of freedom.

Another version of the simulation system **100** according to the present invention comprises a user object **130** capable of detecting the position of the hand of a user, but that does not have to be worn like a glove. Instead, the user may place his or her hand in contact with the user object **130** in order to interact with the graphical environment **110**. For example, as shown in Figure 12, the user object **130** may comprise a mouse **600** which is manipulatable in at least a planar workspace **605** by a user. This version is convenient and inexpensive to implement while still providing an advantageous virtual reality experience to the user. U.S. Patents 6,211,861, 6,100,874, 6,166,723, U.S. Patent Application Serial No. 09/585,741 filed on June 2, 2000, and U.S. Provisional Patent Application 60/224,584 filed on October 11, 2000 describe versions of haptic mice and are incorporated herein by reference in their entireties.

The mouse **600** of Figure 12 adapted to control the graphical image **115** in the graphical environment **110**. Either the entire mouse **600** may serve as the actuatable user object **130** or the housing **615** of the mouse **600** may serve as the actuatable user object **130**. As the

5  mouse **600** is manipulated by a user, its position is detected and the manipulation is communicated to the computer **150** to, for example, control the positioning of the graphical image **115** on a computer screen **155**. Mouse **600** is an object that may be grasped or gripped or otherwise contacted by the hand to be manipulated by a user. By grasp in this context it is meant that users may releasably engage a portion of the object in some fashion, such as by hand,

10  with their fingertips, etc. In the described embodiment, mouse **600** is shaped so that a user's fingers or hand may comfortably grasp the object and move it in the provided degrees of freedom in physical space. For example, a user can move mouse **600** to provide planar two-dimensional input to a computer system to correspondingly move the graphical image **115**, such as a graphical hand. In addition, mouse **600** may includes one or more buttons **620a**, **620b**,

15  **620c**, **620d**, **620e** to allow the user to provide additional commands to the computer **150**, as will be described below. Typically, the mouse **600** is a smooth- or angular-shaped compact unit that is designed to fit under a user's hand, fingers, and/or palm, but can also be implemented as a grip, finger cradle, cylinder, sphere, planar object, etc. or may assume the shape or contour of a portion of a person's body.

20

In the version of Figure 12, the mouse **600** rests on a ground surface **605** such as a tabletop, mousepad, or a platform. A user grasps the mouse **600** and moves the mouse **600** in a planar workspace on the surface **605** as indicated by arrows **630**. Mouse **600** may be moved relative to the ground surface **205**, and in one version may be picked up and placed in a different

25  location. In another version, the mouse **600** is linked to the ground surface **205**. A frictional ball and roller assembly (not shown in Figure 12) can in some embodiments be provided on the underside of the mouse **600** to translate the planar motion of the mouse **600** into electrical position signals, which are sent to the computer **150** over a bus **205** as is well known to those skilled in the art. In other embodiments, different mechanisms and/or electronics can be used to

30  convert mouse motion to position or motion signals received by the computer **150**, as described below. Mouse **600** may be a relative device, in which its sensor detect a change in position of the mouse, allowing the mouse **600** to be moved over any surface at any location. Alternatively, an absolute mouse may also be used, in which the absolute position of the mouse **600** is known with reference to a particular predefined workspace. The bus **205**, which communicates signals

between mouse **600** and computer **150** may also provide power to the mouse **600**. Components such as actuator **135** may require power that can be supplied from a conventional serial port or through an interface such as a USB or Firewire bus. In other embodiments, signals can be sent between mouse **600** and computer **150** by wireless transmission/reception. In some

5  embodiments, the power for the actuator can be supplemented or solely supplied by a power storage device provided on the mouse **600**, such as a capacitor or one or more batteries. Some embodiments of such are disclosed in U.S. Patent No. 5,691,898, which is incorporated herein by reference in its entirety.

10  Mouse **600** may include or be acted on by an actuator **135** which is operative to produce forces on the mouse **600** and thereby provide haptic sensations to the user. The mouse **600** may be either a tactile mouse or a kinesthetic force feedback mouse, or both. In one version a tactile mouse comprises, for example, an actuator **135** positioned within the mouse **600** and outputs a force to the housing **215** of the mouse **600**. This version is particularly useful

15  in providing tactile sensations, such as vibrations, to the user. In one version, the actuator **135** comprises a grounded link that is connected to the mouse **600** to provide kinesthetic force feedback to the mouse **600** in two or more degrees of freedom, for example by forcing the mouse **600** in the direction of arrows **230**. This version is particularly useful in kinesthetically simulating contours and the feel of objects. Each of these versions will be described herein

20  below.

Figure 13 is a side cross-sectional view of a version of the mouse **600** of Figure 12 where the mouse is a tactile mouse **650**. Tactile mouse **650** includes one or more actuators **135** for imparting haptic feedback such as tactile sensations to the user of the tactile mouse **650**.

25  The actuator **135** outputs forces on the tactile mouse **650** which the user is able to feel. The embodiment of Fig. 13 is intended to provide inertial forces rather than contact forces; contact forces are described with respect to Fig. 14. In some embodiments, two or more actuators **135** can provide inertial forces or contact forces, or one actuator **135** can provide inertial forces, while a different actuator **135** can provide contact forces.

30  Tactile mouse **650** includes a housing **615**, a sensing system **655**, and a tactile actuator assembly **660**. Housing **615** is shaped to fit the user's hand like a standard mouse while the user moves the tactile mouse **650** in the planar degrees of freedom and manipulates the buttons **620a-620e**. Other housing shapes can be provided in many different embodiments.

Sensing system **655** detects the position of the tactile mouse **650** in its planar degrees of freedom, e.g. along the X and Y axes. In the described embodiment, sensing system **655** includes any one of known sensing technologies. For example, in the version shown, a

5    standard mouse ball **665** for providing directional input to the computer 150. Ball **665** is a sphere that extends partially out the bottom surface of the tactile mouse **650** and rolls in a direction corresponding to the motion of the tactile mouse **650** on a planar surface **605**. For example, when the tactile mouse **650** is moved in a direction indicated by arrow **670** (y direction), the ball rotates in place in a direction shown by arrow **675**. The ball motion can be

10   tracked by a cylindrical roller **680**, or the like, which is coupled to a sensor **685** for detecting the motion of the mouse **600**. A similar roller and sensor can be used for the x-direction which is perpendicular to the y-axis. Other types of mechanisms and/or electronics for detecting planar motion of the tactile mouse **650** can be used in other embodiments. In some embodiments, high frequency tactile sensations can be applied by the actuator that cause a mouse ball **665** to slip

15   with respect to the frictionally engaged rollers. In another version, an optical sensor that has no moving mouse ball component may be used. A suitable optical mouse technology is made by Agilent of Palo Alto, CA and can be advantageously combined with the tactile sensation technologies described herein, where the optical sensor detects motion of the mouse relative to the planar support surface by optically taking and storing a number of images of the surface and

20   comparing those images over time to determine if the mouse has moved. For example, the IFeel™ mouse device from Logitech Corporation uses this type of sensor.

Buttons **620a-620e** can be selected by the user as a "command gesture" when the user wishes to input a command signal to the computer **150**. The user pushes a button **620**

25   down (in the degree of freedom of the button approximately along axis z) to provide a command to the computer **150**. The command signal, when received by the computer **150**, can manipulate the graphical environment in a variety of ways. In one embodiment, an electrical lead can be made to contact a sensing lead as with any mechanical switch to determine a simple on or off state of the button. An optical switch or other type of digital sensor can alternatively be

30   provided to detect a button press. In a different continuous-range button embodiment, a sensor can be used to detect the precise position of one or more of the buttons **620a-620e** in its range of motion (degree of freedom). In some embodiments, one or more of the buttons **620a-620e** can be provided with force feedback (instead of or in addition to the tactile feedback from actuator **135**), as described in copending U.S. Patent Application Serial No. 09/235,132, filed on

February 18, 1999 and which is incorporated herein by reference in its entirety. In one version, the buttons **620** may be used to control the shape of a graphical image **115**, such as a graphical hand **170**, as will be described below.

5        The tactile actuator assembly **660** may include an actuator assembly including an actuating mechanism **690**, such as a motor, a flexure mechanism ("flexure") **695**, and an inertial mass **700** coupled to the actuating mechanism **690** by the flexure **695**. The inertial mass **700** is moved in a linear direction by the actuating mechanism **690**, for example approximately in the z-axis **705** which is approximately perpendicular the planar workspace of the mouse **600** in the x- and y-axes, e.g. the mouse's position or motion is sensed in the x-y plane. The tactile actuator **660** is coupled to the housing **615** of the tactile mouse **650** such that inertial forces caused by the motion of the inertial mass **700** are applied to the housing **615** of the tactile mouse **650** with respect to the inertial mass, thereby conveying haptic feedback such as tactile sensations to the user of the tactile mouse **650** who is contacting the housing **615**. Thus, the actuating mechanism **690** need not directly output forces to the user or to a user-manipulatable object, but instead the moving mass creates an inertial force that is indirectly transmitted to the user. Thus, the inertial mass is used as a grounding reference for tactile sensations, and the housing **615** may serve as a palm forcing mechanism **180**. Alternatively, the actuating mechanism **690** may directly apply the forces or may be coupled to a rotating eccentric mass.

One version of the tactile mouse **650** provides linear output forces using a rotary actuator, i.e. an actuator outputting a rotary force (torque). In the current actuator market, rotary actuators such as rotary DC motors are among the most inexpensive types of actuators that still allow high bandwidth operation (when driven with signals through, for example, an H-bridge type amplifier). These types of motors can also be made very small and output high magnitude forces for their size. Thus, actuating mechanism **690** may be a DC motor, but can be other types of rotary actuators in other embodiments. For example, a moving magnet actuator can be used instead of a DC motor; such an actuator is described in detail in copending patent application no. 60/133,208, incorporated herein by reference. Other types of actuators can also be used, such as a stepper motor controlled with pulse width modulation of an applied voltage, a pneumatic/hydraulic actuator, a torquer (motor with limited angular range), shape memory alloy material (wire, plate, etc.), a piezo-electric actuator, etc. The tactile mouse **650** in the version shown in Figure 13 makes use of low cost flexure as a mechanical transmission to convert a rotary actuator force to a linear force that is used to move the inertial mass, and to also amplify

the forces to allow more compelling haptic sensations. Versions of the flexure are described in U.S. Patent Application 09/585,741. In the described embodiment of Figure 13, tactile actuator **660** has a stationary portion which is coupled to a part of the housing **615** (and thus stationary only with respect to the portion of the mouse housing to which it is coupled), for example by

5 being coupled to bottom portion **710** of the housing **615**. A rotating shaft of the actuating mechanism **690** is coupled to the moving portion of the assembly that includes the inertial mass **700** and at least part of the flexure **695**, where the inertial mass moves linearly approximately along the Z-axis. The actuating mechanism **690** is operative to oscillate the inertial mass **700** (or itself in some embodiments) quickly along an axis which is approximately parallel to the Z

10 axis. Thus, forces produced by the oscillation of the inertial mass **700** are transmitted to the housing **615** through the tactile actuator **660** and felt by the user.

Alternatively, directed inertial forces can be output along the X and Y axes in the planar workspace of the device and can be compensated for to prevent or reduce interference with the user's control of the device. One method to compensate is to actively filter imparted

15 jitter in that workspace, as disclosed in U.S. Patent No. 6,020,876 which is incorporated herein by reference in its entirety. The x and y directed tactile sensations may also provide advantageous and authentic virtual reality related tactile sensations.

One way to direct an inertial force is to directly output a linear force, e.g., a linear moving voice coil actuator or a linear moving-magnet actuator can be used, which are suitable for high bandwidth actuation. These embodiments are described in greater detail in U.S. Patent No. 6,211,861 which is incorporated herein by reference in its entirety. These embodiments allow for high fidelity control of force sensations in both the frequency and

25 magnitude domains, and also allow the forces to be directed along a desired axis and allows for crisp tactile sensations that can be independently modulated in magnitude and frequency.

Figure 14 is a side elevational view of another version of a tactile mouse **650'**. In this version, the linear motion provided by the tactile actuator **660** is used to drive a portion

30 of the housing **615** (or other member) that is in direct contact with the user's hand (finger, palm, etc.). The tactile actuator **660** of this version includes an actuating mechanism **690**, flexure **695**, and inertial mass similar to the version of Figure 13 (except that the actuating mechanism and flexure of Fig. 14 are shown rotated approximately 90 degrees with respect to Fig. 13). The tactile mouse **650'** of Figure 14 includes a moving cover portion **720** which can be part of the

housing **615**. Cover portion **720** is coupled to the rest of the housing **615** by a hinge allowing their respective motion, such as a mechanical hinge, a flexure, rubber bellows, or other type of hinge. Cover portion **720** may thus rotate about an axis B of the hinge. In other embodiments, the hinge can allow linear or sliding motion rather than rotary motion between cover and

5 housing portions. In the embodiment shown, the cover portion **720** extends in the y-direction from about the mid-point of the mouse housing to near the back end of the tactile mouse **650'**. In other embodiments, the cover portion **720** can cover larger or smaller areas. Various embodiments of such a moveable cover portion are described in copending patent application no. 09/253,132 which is incorporated herein by reference in its entirety. The cover portion **720**

10 is rotatably coupled to a link **725**, and the link **725** is rotatably coupled at its other end to the linear moving portion the flexure **695**. Thus, as the member of the flexure **695** is moved along the z-axis, this motion is transmitted to the cover portion **720** through the link **725**, where the rotational couplings of the link allow the cover portion **720** to move about axis B of the hinge. The actuating mechanism **690** can drive the flexure **695** up on the z-axis, which causes the cover

15 portion **720** to move up to, for example, the dashed position shown.

The user feels the force of the cover portion **720** against his or her hand (such as the palm) as a contact force (as opposed to an inertial force). When the cover portion is oscillated, the user can feel a vibration-like force. Accordingly, the cover portion **720** may be

20 used as a palm forcing mechanism **180** to simulate a contact sensation at the palm. The cover portion can also be used to designate 3-D elevations in a graphical environment. In some embodiments, the configuration described can inherently provide an inertial force as well as the contact force if an inertial mass is moved as described above in addition to the contact portion. In other embodiments, a different "contact member" (e.g. a member that is physically contacted

25 by the user) can be moved instead of the cover portion **320** but in a similar fashion, such as one or more of the mouse buttons **620a-620e** or other buttons, tabs, mouse wheels, or dials. Furthermore, in some embodiments multiple actuator assemblies can be used to drive a cover portion and one or more buttons **620a-620e** or other controls of the tactile mouse **250'**. Furthermore, in some embodiments, one actuator assembly can be used to move a cover portion

30 **720** or other member, and a different actuator assembly can be used to provide an inertial force as in the embodiment of Figure 13, where the inertial and contact forces can operate in conjunction if desired.

Figure 15 is a block diagram illustrating one embodiment of the simulation

system **100** where the controller **125** may comprise a computer **150** and the haptic interface device **140** may comprise a tactile mouse **650**, such as one of the tactile mice discussed above. In this version, the tactile mouse **650** comprises a local microprocessor **750**. However, the invention may be implemented with higher level control.

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The computer **150** may include a processor **755**, such as a microprocessor, a clock **760**, a display screen **155**, and an audio output device **765**. The computer **150** may also include other well known components, such as random access memory (RAM), read-only memory (ROM), and input/output (I/O) electronics (not shown). Display screen **155** displays

10 images of a simulation, game environment, operating system application, etc. Audio output device **765**, such as speakers, is preferably coupled to host microprocessor **755** via amplifiers, filters, and other circuitry well known to those skilled in the art and provides sound output to user when an "audio event" occurs during the implementation of an application program. Other types of peripherals can also be coupled to host processor **755**, such as storage devices (hard

15 disk drive, CD ROM drive, floppy disk drive, etc.), printers, and other input and output devices.

The haptic interface device **140**, such as a tactile mouse **250**, is coupled to the computer **150** by a bi-directional bus **205**. The bi-directional bus **205** sends signals in either direction between the computer **150** and the interface device **140**. Bus **205** can be a serial

20 interface bus, such as an RS232 serial interface, RS-422, Universal Serial Bus (USB), MIDI, or other protocols well known to those skilled in the art, or a parallel bus or wireless link. For example, the USB standard provides a relatively high speed interface that can also provide power to the actuator **135**.

25 The haptic interface device **140**, such as the tactile mouse **250** can include a local controller, such as a local microprocessor **750**. Local microprocessor **750** can optionally be included within the housing **615** of the tactile mouse **650** to allow efficient communication with other components of the tactile mouse **650**. By local it is meant that the processor **750** is a separate processor from any processors in the computer **150**. The local microprocessor **750** may

30 be dedicated to haptic feedback and sensor I/O of the tactile mouse **650**. Local microprocessor **750** can be provided with software instructions to wait for commands or requests from the computer **150**, decode the command or request, and handle/control input and output signals according to the command or request. In addition, local processor **750** can operate independently of the computer **150** by reading sensor signals and calculating appropriate forces

from those sensor signals, time signals, and stored or relayed instructions selected in accordance with a host command. Suitable microprocessors for use as local microprocessor 750 include the MC68HC711E9 by Motorola, the PIC16C74 by Microchip, and the 82930AX by Intel Corp., for example, as well as more sophisticated force feedback processors such as the Immersion

5      Touchsense Processor, available from Immersion Corporation in San Jose, California. Local microprocessor 750 can include one microprocessor chip, multiple processors and/or co-processor chips, and/or digital signal processor (DSP) capability.

         Local microprocessor 750 can receive signals from sensor(s) 770 and provide

10     signals to tactile actuator 660 in accordance with instructions provided by the computer 150 over bus 205. For example, in a local control embodiment, the computer 150 provides high level supervisory commands to local microprocessor 750 over bus 205, and local microprocessor 750 decodes the commands and manages low level force control loops to sensors 770 and the tactile actuator 660 in accordance with the high level commands and

15     independently of the computer 150. This operation is described in greater detail in US Patents 5,739,811 and 5,734,373, both incorporated by reference herein in their entireties. In the computer control loop, force commands are output from the computer 150 to local microprocessor 750 and instruct the local microprocessor 750 to output a force or force sensation having specified characteristics. The local microprocessor 750 reports data to the

20     computer 150, such as locative data that describes the position of the tactile mouse 650 in one or more provided degrees of freedom. The data can also describe the states of buttons 620a-620e and a safety switch 775. The computer 150 uses the data to update executed programs. In the local control loop, actuator signals are provided from the microprocessor 750 to tactile actuator 660 and sensor signals are provided from the sensor 770 and other input devices 780 to the local

25     microprocessor 750. The haptic sensation or tactile sensation may be either a single force or a sequence of forces output by the tactile actuator 660 which provide a sensation to the user. For example, vibrations, a single jolt or pulse, or a texture sensation are all considered haptic or tactile sensations. The local microprocessor 750 can process inputted sensor signals to determine appropriate output actuator signals by following stored instructions. The

30     microprocessor 750 may use sensor signals in the local determination of forces to be output on the housing 615, as well as reporting locative data derived from the sensor signals to the host computer.

         In yet other embodiments, other simpler hardware can be provided locally to

tactile mouse **650** to provide functionality similar to microprocessor **750**. For example, a hardware state machine incorporating fixed logic can be used to provide signals to the tactile actuator **660** and receive sensor signals from sensors **770**, and to output tactile signals according to a predefined sequence, algorithm, or process. Techniques for implementing logic with desired functions in hardware are well known to those skilled in the art.

In a different, host-controlled embodiment, the computer **150** can provide low-level force commands over bus **205**, which are directly transmitted to the tactile actuator **660** via local microprocessor **750** or other (e.g. simpler) circuitry. The computer **150** thus directly controls and processes all signals to and from the tactile mouse **650**, e.g. the computer **150** directly controls the forces output by tactile actuator **660** and directly receives sensor signals from sensor **770** and input devices **780**. This embodiment may be desirable to reduce the cost of the haptic feedback device yet further, since no local microprocessor **750** or other processing circuitry need be included in the tactile mouse **650**. In another simple host control embodiment, the signal from the host to the device can be a single bit that indicates whether to actuate the actuator at a predefined frequency and magnitude. In a more complex embodiment, the signal from the host could include a magnitude, giving the strength of the desired actuation. In yet a more complex embodiment, the signal can include a direction, giving both a magnitude and a sense for the actuation. In still a more complex embodiment, a local processor can be used to receive a simple command from the host that indicates a desired force value to apply over time. The microprocessor then outputs the force value for the specified time period based on the one command, thereby reducing the communication load that must pass between host and device. In an even more complex embodiment, a high-level command with tactile sensation parameters can be passed to the local processor **750** on the device which can then apply the full sensation independent of host intervention. Such an embodiment allows for the greatest reduction of communication load. Alternatively, a combination of numerous methods described above can be used for a single tactile mouse **650**.

Local memory **780**, such as RAM and/or ROM, is preferably coupled to microprocessor **750** in tactile mouse **650** to store instructions for microprocessor **750** and store temporary and other data. For example, force profiles can be stored in memory **780**, such as a sequence of stored force values that can be output by the microprocessor, or a look-up table of force values to be output based on the current position of the tactile mouse **650**. In addition, a local clock **785** can be coupled to the microprocessor **750** to provide timing data, similar to the

system clock of the computer **150**; the timing data might be required, for example, to compute forces output by tactile actuator **660** (e.g., forces dependent on calculated velocities or other time dependent factors). In embodiments using the USB communication interface, timing data for microprocessor **750** can be alternatively retrieved from the USB signal. For example, the computer **150** can send a "spatial representation" to the local microprocessor **750**, which is data describing the locations of some or all the graphical objects **120** displayed in a graphical environment **110** which are associated with forces and the types/characteristics of these graphical objects **120**. The microprocessor **750** can store such a spatial representation in local memory **780**, and thus will be able to determine interactions between the user object and graphical objects **120** independently of the computer **150**. In addition, the microprocessor **750** can be provided with the necessary instructions or data to check sensor readings, determine graphical image **115** positions, and determine output forces independently of the computer **150**. The computer **150** could implement program functions (such as displaying images) when appropriate, and synchronization commands can be communicated between the microprocessor and the computer **150** to correlate the microprocessor and host processes. Also, the local memory **780** can store predetermined force sensations for the microprocessor that are to be associated with particular types of graphical objects. Alternatively, the computer **150** can directly send force feedback signals to the tactile mouse **650** to generate tactile sensations.

Sensors **770** sense the position or motion of the mouse (e.g. the housing **615**) in its planar degrees of freedom and provides signals to microprocessor **750** (or to computer **150**) including information representative of the position or motion. Sensors suitable for detecting planar motion of a tactile mouse include the sensing system **655** described above for Fig. 13, e.g. digital optical encoders frictionally coupled to a rotating ball or cylinder, as is well known to those skilled in the art. Optical sensor systems, linear optical encoders, potentiometers, optical sensors, velocity sensors, acceleration sensors, strain gauge, or other types of sensors can also be used, and either relative or absolute sensors can be provided. Optional sensor interface **790** can be used to convert sensor signals to signals that can be interpreted by the microprocessor **750** and/or computer **150**, as is well known to those skilled in the art.

Tactile actuator **660** transmits forces to the housing **615** of the tactile mouse **650** as described above with reference to Figures 13 and 14 in response to signals received from microprocessor **750** and/or computer **150**. Tactile actuator **660** is provided to generate inertial forces by moving an inertial mass, and/or contact forces by moving a contact member such as a

cover portion **720**. The tactile actuator **660** has the ability to apply a short duration force on the housing **615** of the mouse with respect to an inertial mass. In one version, this short duration is directed substantially along a Z axis orthogonal to the X-Y plane of motion of the tactile mouse **650**. The short duration force may be a single burst of fixed magnitude and duration or may be

5   controllable and/or shapeable. In one version, a periodic force can be applied to the housing of the tactile mouse **650** with respect to the inertial mass, where the periodic force can have a magnitude and a frequency, e.g. a sine wave; the periodic sensation can be selectable among a sine wave, square wave, saw-toothed-up wave, saw-toothed-down, and triangle wave; an envelope can be applied to the period signal, allowing for variation in magnitude over time; and

10   the resulting force signal can be "impulse wave shaped" as described in U.S. Patent No. 5,959,613 which is incorporated herein by reference in its entirety. There are two ways the period sensations can be communicated from the host to the device. The wave forms can be "streamed" as described in U.S. Patent 5,959,613 and pending provisional patent application 60/160,401, both incorporated herein by reference in their entireties. Or the waveforms can be

15   conveyed through high level commands that include parameters such as magnitude, frequency, and duration, as described in U.S. Patent 5,734,373 which is incorporated herein by reference in its entirety. These control schemes can also apply when providing contact forces using a moveable member. A short duration force command signal can also be used in those embodiments outputting both inertial and contact forces to move both the inertial mass and the

20   contact member to provide simultaneous pulse sensations; or, the inertial mass can be controlled to output one sensation and the contact member can be simultaneously controlled to output a different sensation, such as a force of a different duration or magnitude, a vibration of a different frequency, a texture of a different spacing, etc.

25   Alternate embodiments can employ additional actuators for providing haptic sensations in the z-direction and/or in the degrees of freedom of the tactile mouse **650**. In one embodiment, the tactile mouse **650** can include multiple tactile actuators for greater magnitude forces, forces in multiple degrees of freedom, and/or different simultaneous haptic sensations. In another embodiment, the tactile mouse **650** can be enhanced with a secondary, different type

30   of actuator in addition the actuator assembly described herein. Because of power constraints in some embodiments, this secondary actuator can be passive (i.e., it dissipates energy). The passive actuator can be a brake, e.g., a brake employing a very low power substrate such as a magneto-rheological fluid. Alternatively, it can be a more traditional magnetic brake. The passive braking means can be employed through a frictional coupling between the mouse

housing **615** and the table surface **605**. For example, a friction roller in the mouse housing base can engage the table surface. The roller can spin freely when the mouse is moved by the user so long as the passive brake is not engaged. When the brake is engaged, the user can feel the passive resistance to motion of the mouse (in one or two of the planar degrees of freedom of the

5    mouse).

Actuator interface **795** can be optionally connected between tactile actuator **660** and local microprocessor **750** to convert signals from microprocessor **750** into signals appropriate to drive tactile actuator **660**. Actuator interface **795** can include power amplifiers,

10    switches, digital to analog controllers (DACs), analog to digital controllers (ADCs), and other components, as is well known to those skilled in the art. It should be noted that circuitry should be provided to allow the actuator to be driven in two directions, since the preferred embodiment does not allow full revolutions of the actuator shaft, as described above. Circuitry for such bi-directional (harmonic) operation are well known to those skilled in the art and are also described

15    in copending provisional patent application no. 60/142,155, incorporated herein by reference in its entirety.

Other input devices **780** may be included in the tactile mouse **650** and send input signals to microprocessor **750** or to the computer **150** when manipulated by the user. Such input

20    devices include buttons **620a-620e** and can include additional buttons, dials, switches, scroll wheels, or other controls or mechanisms.

Power supply **797** can optionally be included in tactile mouse **650** coupled to actuator interface **795** and/or tactile actuator **660** to provide electrical power to the actuator, or

25    may be provided as a separate component. Alternatively, and more preferably when possible, power can be drawn from a power supply separate from the tactile mouse **650**, or power can be received across a USB or other bus. Also, received power can be stored and regulated by tactile mouse **650** and thus used when needed to drive tactile actuator **660** or used in a supplementary fashion. Because of the limited power supply capabilities of USB, a power storage device may

30    be required in the mouse device to ensure that peak forces can be applied (as described in U.S. Patent No. 5,929,607, incorporated herein by reference in its entirety). For example, power can be stored over time in a capacitor or battery and then immediately dissipated to provide a jolt sensation to the mouse. Alternatively, this technology can be employed in a wireless mouse, in which case battery power is used to drive the tactile actuator **660**. In one embodiment, the

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battery can be charged by an electric generator on board the mouse, the generator driven by the user's motions of the mouse device. For example, a mouse ball or cylinder can turn a frictional roller or shaft that is coupled to and recharges the generator.

5      A safety switch **775** can optionally be included to allow a user to deactivate tactile actuator **660** for safety reasons. For example, the user must continually activate or close safety switch **775** during operation of tactile mouse **650** to enable the tactile actuator **660**. If, at any time, the safety switch is deactivated (opened), power from power supply **797** is cut to tactile actuator **660** (or the actuator is otherwise disabled) as long as the safety switch is needed.

10     Embodiments include an optical switch, an electrostatic contact switch, a button or trigger, a hand weight safety switch, etc.

A number of tactile sensations can be output by the tactile mouse **650**. A basic tactile functionality desired for the tactile mouse **650** is a jolt sensation. A jolt sensation may be

15     output when the graphical image **115** is moved to a position where it intersects the graphical object **120** or moved to a position where is lies within or near a predetermined region of the graphical object **120**. The appropriate sensation for this simple interaction is a quick, abrupt pop. This can be achieved by applying a crisp, short force between the inertial mass and the housing of the mouse device, e.g. by moving the inertial mass in one or a small number of

20     oscillations. For example, a jolt can include a single impulse of force that quickly rises to a desired magnitude and then is turned off or quickly decays back to zero or small magnitude. The pulse can also or alternatively be output as a motion up and down of a contact member such as a cover portion of the housing of the mouse, in appropriate embodiments. A vibration can also be output, which can include a series of jolts or pops applied periodically over a particular

25     time period at a particular frequency. The time-varying force can be output according to a force vs. time waveform that is shaped like a sine wave, triangle wave, sawtooth wave, or other shape of wave. The vibration is caused by a mass or contact member oscillating back and forth. In some embodiments, the sensation of a "spatial texture" may be output by correlating jolts and/or vibrations with the motion of the cursor over a graphical object or area. This type of force can

30     depend on the position of the tactile mouse **650** in its planar workspace (or on the position of the graphical image **115** in the graphical environment **110**). For example, the graphical image **115** can be dragged over a graphical grating and jolts can be correlated with the spacing of the grating openings. Thus, texture bumps are output depending on whether the graphical image **115** has moved over the location of a bump in a graphical object; when the mouse is positioned

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between "bumps" of the texture, no force is output, and when the mouse moves over a bump, a force is output. This can be achieved by host control (e.g., the host computer 150 sends the jolts as the graphical image 115 is dragged over the grating) or by local control (e.g., the host computer 150 sends a high level command with texture parameters and the sensation is directly

5      controlled by the tactile mouse 250 device). Some methods for providing texture sensations in a tactile sensation device are described in copending application no. 09/504,201, filed 2/15/00 and incorporated herein by reference in its entirety. In other cases, a texture can be performed by presenting a vibration to a user, the vibration being dependent upon the current velocity of the tactile mouse 650 in its planar workspace 605. When the tactile mouse 650 is stationary, the

10     vibration is deactivated; as the mouse moves faster, the frequency and magnitude of the vibration is increased. This sensation can be controlled locally by the device processor 750, or be controlled by the computer 150. Local control by the device may eliminate communication burden in some embodiments. Other spatial force sensations besides textures can also be output. In addition, any of the described haptic sensations herein can be output by tactile

15     actuator 660 simultaneously or otherwise combined as desired.

In another version of the invention the simulation system 100 may comprise a haptic interface 140 comprising a version of a mouse 600 that has kinesthetic force feedback capabilities. Figure 16 shows a kinesthetic force feedback mouse 800 to which one or more

20     grounded forces may be applied, for example by being applied in the lateral or the x and y directions.

Figure 16 is a perspective view of a kinesthetic force feedback mouse 800 (hereinafter force feedback mouse 800) as a user object 130 and optionally as part of a haptic

25     interface 140 according to an embodiment of the present invention. The force feedback mouse 800 in this version is movable in relation to another portion of the interface device 140.

Force feedback mouse 800 is an object that is preferably grasped or gripped or contacted to be manipulated by a user, as discussed above in connection with the tactile mouse

30     650. For example, images may be displayed and/or modified on the display screen 155 of the computer 150 in response to such manipulations. In the described embodiment, force feedback mouse 800 is shaped so that a user's fingers or hand may comfortably grasp the object and move it in the provided degrees of freedom in physical space. For example, a user can move force feedback mouse 800 to correspondingly move a computer generated graphical object, such

as a cursor or other image, in a graphical environment provided by the computer **150**. The available degrees of freedom in which force feedback mouse **800** can be moved are determined from the haptic interface, described below. In addition, force feedback mouse **800** may include one or more buttons **620a-620e**, as described above and to be described in further detail below, to allow the user to provide additional commands to the computer **150**. The force feedback mouse **800** may also include additional buttons.

Electronic interface **810** interfaces mechanical and electrical input and output between the force feedback mouse **800** and the computer **150** implementing the application program, such as the simulation, a GUI, or game environment. Electronic interface **810** provides multiple degrees of freedom to force feedback mouse **800**; in the preferred embodiment, two linear, planar degrees of freedom are provided to the mouse, as shown by arrows **630**. In other embodiments, greater or fewer degrees of freedom can be provided, as well as rotary degrees of freedom.

In one version, the user manipulates force feedback mouse **800** in a planar workspace, much like a traditional mouse, and the position of force feedback mouse **800** is translated into a form suitable for interpretation by position sensors of the electronic interface **810**. The sensors track the movement of the force feedback mouse **800** in planar space and provide suitable electronic signals to an electronic portion of electronic interface **810**. The electronic interface **810** provides position information to the computer **150**. In addition, the computer **150** and/or electronic interface **810** provide force feedback signals to actuators coupled to electronic interface **810**, and the actuators generate forces on members of the mechanical portion of the electronic interface **810** to provide forces on force feedback mouse **800** in provided or desired degrees of freedom. The user experiences the forces generated on the force feedback mouse **800** as realistic simulations of force sensations such as jolts, springs, textures, "barrier" forces, and the like. Since the housing of the force feedback mouse **800** is in contact with the palm of a user, the force feedback mouse housing may serve as a palm forcing mechanism **180**.

The electronic portion of electronic interface **810** may couple the mechanical portion of the interface to the computer **150**. The electronic portion may be included within the housing **815** of the electronic interface **810** or, alternatively, the electronic portion may be included in the computer **150** or as a separate unit with its own housing. Electronic interface

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**810** may include a local microprocessor distinct and separate from a microprocessor in the computer **150**. The local microprocessor may be used to control force feedback on force feedback mouse **800** independently of the host computer, as well as sensor and actuator interfaces that convert electrical signals to appropriate forms usable by the mechanical portion

5    of electronic interface **810** and the computer **150**. For example, a rigid surface may be generated on computer screen **155** and a graphical image **115** controlled by the user may be caused to interact with, for example by intersecting, the surface. In this embodiment, high-level host commands can be used to provide the various forces associated with the rigid surface. The local control mode using a local microprocessor in electronic interface **810** can be helpful in

10   increasing the response time for forces applied to the user object, which is essential in creating realistic and accurate force feedback. For example, the computer **150** may send a "spatial representation" to the local microprocessor, which is data describing the locations of some or all the graphical objects displayed in a graphical environment **110** which are associated with forces and the types/characteristics of graphical objects, such as a graphical object **120**, in the

15   graphical environment **110**. The microprocessor can store such a spatial representation in local memory, and thus will be able to determine interactions between the user object and graphical objects (such as the rigid surface) independently of the computer **150**. In addition, the microprocessor can be provided with the necessary instructions or data to check sensor readings, determine cursor and target positions, and determine output forces independently of

20   the computer **150**. The computer **150** could implement program functions (such as displaying images) when appropriate, and synchronization commands can be communicated between the microprocessor and computer **150** to correlate the microprocessor and computer processes. Also, the local memory can store predetermined force sensations for the microprocessor that are to be associated with particular types of or portions of the graphical object **120**. Alternatively,

25   the computer **150** can directly send force feedback signals to the electronic interface **810** to generate forces on force feedback mouse **800**.

The electronic interface **810** can be coupled to the computer **150** by a bus **205**, which communicates signals between electronic interface **810** and computer **150** and also may

30   provide power to the electronic interface **810** (e.g. when bus **205** includes a USB interface). In other embodiments, signals can be sent between electronic interface **810** and computer **150** by wireless transmission/reception. In an embodiment of the present invention, the electronic interface **810** serves as an input/output (I/O) device for the computer **150**. The electronic interface **810** can also receive inputs from other input devices or controls that are associated

with the haptic interface **140** and can relay those inputs to the computer **150**. For example, commands sent by the user activating a button on force feedback mouse **800** can be relayed to computer **150** by electronic interface **810** to implement a command or cause the computer **150** to output a command to the electronic interface **810**.

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There are two primary "control paradigms" of operation for the force feedback mouse **800**: position control and rate control. Position control is the more typical control paradigm for mouse and similar controllers, and refers to a mapping of force feedback mouse **800** in which displacement of the force feedback mouse **800** in physical space directly dictates displacement of the graphical image **115**. The mapping can have an arbitrary scale factor or even be non-linear, but the fundamental relation between mouse displacements and graphical object displacements should be present. Under a position control mapping, the graphical image **115** does not move unless the force feedback mouse **800** is in motion. Position control is commonly used for virtual reality simulations. Position control force feedback roughly corresponds to forces which would be perceived directly by the user, i.e., they are "user-centric" forces. Also, "ballistics" or other non-linear adjustments to cursor position can be used, in which, for example, small motions of the mouse have a different scaling factor for cursor movement than large motions of the mouse, to allow more control of small cursor movement. As shown in Figure 16, the computer **150** may have its own "host frame" which is displayed on the display screen **155** and represented by the coordinates u,v. In contrast, the force feedback mouse **800** has its own "local frame" in which the force feedback mouse **800** is moved and represented by coordinates x,y. In a position control paradigm, the position (or change in position) of a user-controlled graphical object, such as a cursor, in host frame corresponds to a position (or change in position) of the force feedback mouse **800** in the local frame. The offset between the object in the host frame and the object in the local frame can be changed by the user for. Rate control may also or alternatively be also used as a control paradigm. This refers to a mapping in which the displacement of the force feedback mouse **800** along one or more provided degrees of freedom is abstractly mapped to motion of a computer-simulated object under control. There is not a direct physical mapping between physical object (mouse) motion and computer object motion. Thus, most rate control paradigms are fundamentally different from position control in that the user object can be held steady at a given position but the controlled computer object is in motion at a commanded or given velocity, while the position control paradigm only allows the controlled computer object to be in motion if the user object is in motion.

Force feedback mouse **800** may be supported upon a grounded pad **820** which helps define the planar workspace **605**. Pad **820** or a similar surface is supported by grounded surface **825**. Force feedback mouse **800** contacts grounded pad **820** (or alternatively grounded surface **825**) to provide additional support for the mouse and relieve stress on any mechanical support structures.

The haptic interface comprising a force feedback mouse may also include an indexing function or "indexing mode" which allows the user to redefine the offset between the positions of the force feedback mouse **800** in the local frame and a graphical image **115**, in the host frame displayed by the computer **150**. Indexing is inherently provided with a traditional position control device such as a standard mouse. When a physical limit to the mouse's movement is reached, the user typically lifts the mouse from the contacted surface and places the mouse in a different position to allow more room to move the mouse. While the mouse is off the contacted surface, no input is provided to control the graphical image. Force feedback mouse **800** of the present invention also has a limit to movement in the provided planar workspace provided by a guide opening, as detailed below. To allow movement of the graphical image in the host frame past the limits of the mouse local frame, "indexing" is implemented. In one implementation, the user may reposition the force feedback mouse **800** without moving the controlled graphical image or providing any other input to the computer, thus allowing the user to redefine the offset between the object's position and the graphical image's position. This is analogous to standard mouse indexing. In the present invention, such indexing is achieved through an input device such as a button, or alternatively using switches, pressure sensors, optical sensors, contact sensors, voice recognition hardware, or other input devices. As long as the indexing button or device is activated, the force feedback mouse **800** is in indexing mode and can be moved without providing any input to the host computer (e.g., without moving the controlled graphical object). When the button is released (or indexing mode otherwise exited), the position of the graphical image is again controlled by the position of the force feedback mouse **800**. Alternatively, the user might toggle indexing mode and non-indexing mode with one press of a button or other input device. Indexing mode can be performed directly by the computer **150**, or a local microprocessor can perform the indexing function. For example, the local processor can determine when indexing mode is active, and simply not report the position of the force feedback mouse **800** to the computer **150** while such mode is active. A hand weight switch may also be provided for indexing purposes, as described

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in U.S. Patents 5,825,308 and 6,100,874, both of which are incorporated herein by reference in their entireties.

5        Figure 17A is a perspective view of an embodiment of the haptic interface **140** with the cover portion of housing **815** and the grounded pad **820** removed. Force feedback mouse **800** is coupled to a mechanical interface **830**, which includes a mechanical linkage **835** that is coupled to a transducer assembly **840**. A base **845** is provided to support the mechanical linkage **835** and transducer assembly **840** on grounded surface **825**. In the described embodiment, the linkage **835** allows force feedback mouse **800** two planar degrees of freedom

10      in the directions of arrows **630**, and the members of the linkage **835** move approximately within a plane. The linkage is preferably coupled to grounded base **845** at an axis of rotation, described below. The transducer assembly **840** is coupled to base **845** and is thus also grounded.

15      In the described embodiment, at least part of the electronic interface **810** is positioned above the transducer assembly **840**. For example, a printed circuit board **850** or similar support can be positioned over the top surface of transducer assembly **840**. A number of integrated circuits and other components **855** can be coupled to the printed circuit board **850**. This configuration allows the transducer assembly **840** and the electronic interface **810** to

20      conform to a small volume which reduces the overall size of housing **815** and allows the mouse interface device to be positioned in convenient areas of a desktop or other area accessible to a user.

25      Figure 17B is a perspective view of a portion of the mouse device **800** of Figure 16 showing the mechanical interface **830** for providing mechanical input and output in accordance with the present invention. Mechanical linkage **835** provides support for force feedback mouse **800** and couples the mouse to a grounded surface **825**, such as a tabletop or other support. Linkage **835** is, in the described embodiment, a 5-member (or "5-bar") linkage including a base **845**, a first base member **860** coupled to base **845**, a second base member **865**

30      coupled to base **845**, a first link member **870** coupled to first base member **860**, and a second link member **875** coupled to first link member **870** and second base member **865**. In the described embodiment, the first base member **860** and the first link member **870** are arranged generally symmetric to the second base member **865** and the second link member **875** across an axis extending perpendicularly through axes A and D. The symmetrical orientation of the

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members allows first base member **860** and first link member **870**, in some embodiments, to be manufactured substantially in identical fashion as second base member **865** and second link member **875**, thus saving on manufacturing costs. Force feedback mouse **800** is coupled to the linkage at the coupling between link members **870, 875**. Fewer or greater numbers of members in the linkage can be provided in alternate embodiments. Base **845** of the linkage **835** is a base for the support of the linkage and is coupled to or resting on a ground surface **825**. The base **845** in Figure 11b is shown as a plate or base that extends under force feedback mouse **800**.

The members of linkage **835** are rotatably coupled to one another through the use of rotatable pivots or bearing assemblies having one or more bearings, all referred to as "bearings" herein. Linkage **835** is rotatably coupled to base **845** by a grounded bearing **880** and can rotate about an axis A. First link member **870** is rotatably coupled to first base member **860** by bearing **885** and can rotate about a floating axis B, and first base member **865** is rotatably coupled to base **845** by bearing **880** and can rotate about axis A. Second link member **875** is rotatably coupled to second base member **865** by bearing **890** and can rotate about floating axis C, and second link member **875** is also rotatably coupled to first link member **870** by bearing **895** such that second link member **875** and first link member **870** may rotate relative to each other about floating axis D. In an alternate embodiment, a parallel linkage may be used as disclosed in U.S Patent 6,100,874, which is incorporated herein by reference in its entirety. The axes B, C, and D are "floating" in the sense that they are not fixed in one position relative to ground surface **825** as is axis A. Since the only connection of the four linkage members to the base **845** is through grounded bearing **880**, only base members **860, 865** are grounded at axis A. Bearings **885, 890**, and **895** are floating and not connected to the ground member. Preferably, the axes B, C, and D are all substantially parallel to each other.

Linkage **835** is formed as a five-member closed-loop chain. Each member in the chain is rotatably coupled to two other members of the chain. The five-member linkage is arranged such that the members can rotate about their respective axes to provide force feedback mouse **800** with two degrees of freedom, i.e., force feedback mouse **800** can be moved within a planar workspace defined by the x-y plane, which is defined by the x- and y-axes as shown in Figure 17B. Linkage **835** is thus a "planar" five-member linkage, since it allows the force feedback mouse **800** to be moved within a plane. In addition, in the described embodiment, the members of linkage **835** are themselves approximately oriented in a plane.

Force feedback mouse **800** in this embodiment is coupled to link members **870,**
**875** by rotary bearing **895**, for example at attachment plate **900**. The mouse may also preferably
rotate about floating axis D and allow the user some flexible movement in the planar
workspace. The allowed rotation can provided to allow the user's hand/wrist to conveniently

5     stay in one position during mouse movement while the force feedback mouse **800** rotates about
axis D. In alternate embodiments, mouse rotation about axis D may be sensed by sensors. In
yet other embodiments, forces can be provided on force feedback mouse **800** about axis D using
actuators. In the preferred embodiment, a pad or other support is provided under force feedback
mouse **800** to help support the force feedback mouse **800**, and is described in greater detail with

10     respect to Figure 17C.

Transducer assembly **840** is used to sense the position of force feedback mouse
**800** in its workspace and to generate forces on the force feedback mouse **800**. Transducer
assembly **840** may include one or more sensors **905a**, **905b** and/or one or more actuators **910a**,
**910b**. The sensors **905a**, **905b** collectively sense the movement of the force feedback mouse
**800** in the provided degrees of freedom and send appropriate signals to the electronic interface
**810**. Sensor **905a** senses movement of second base member **865** about axis A, and sensor **905b**
senses movement of first base member **860** about axis A. These sensed positions about axis A
allow the determination of the position of force feedback mouse **800** using known constants

20     such as the lengths of the members of linkage **835** and using well-known coordinate
transformations. Member lengths particular to the interface device can be stored in a memory,
such as EEPROM, to account for manufacturing variations among different interface devices;
alternatively, variations of the particular link lengths from standard lengths can be stored in
memory.

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Sensors **905a**, **905b** are, in the described embodiment, grounded optical encoders
that sense the intermittent blockage of an emitted beam. A grounded emitter/detector portion
**915** includes an emitter that emits a beam which is detected by a grounded detector. A moving
encoder disk portion or "arc" is provided at the end of members **860, 868** which each block the

30     beam for the respective sensor in predetermined spatial increments and allows a processor to
determine the position of the arc and thus the members **860, 865** by counting the spatial
increments. Also, a velocity of members **860, 865** based on the speed of passing encoder marks
can also be determined. In one embodiment, dedicated electronics such as a "haptic
accelerator" may determine velocity and/or acceleration, as disclosed in U.S. Patent 5,999,168

which is incorporated herein by reference in its entirety.

In the version shown, transducer assembly **840** also includes actuators **910a,**
**910b** to transmit forces to force feedback mouse **800** in space, i.e., in two (or more) degrees of
freedom of the user object. The bottom housing plate **920** of actuator **910a** is rigidly coupled to
base **845** (or grounded surface **825**) and a moving portion of actuator **910a** (for example a coil)
is integrated into the base **845**. The actuator **910a** transmits rotational forces to first base
member **860** about axis A. The housing **920** of the grounded portion of actuator **910b** is rigidly
coupled to base **845** or ground surface **825** through the grounded housing of actuator **910b**, and
a moving portion (for example a coil) of actuator **910b** is integrated into second base member
**865**. Actuator **910b** transmits rotational forces to second base member **865** about axis A. The
combination of these rotational forces about axis A allows forces to be transmitted to force
feedback mouse **800** in all directions in the planar workspace provided by linkage **835** through
the rotational interaction of the members of linkage **835**.

The operation of exemplary sensors **905a, 905b** and actuators **910a, 910b** are
described in greater detail in U.S. Patents 5,166,723 and 5,100,874, both of which are
incorporated herein by reference in their entireties. Additional and/or different mechanisms can
also be employed to provide desired degrees of freedom to force feedback mouse **800**. This
rotational degree of freedom can also be sensed and/or actuated, if desired, to provide an
additional control degree of freedom. In other embodiments, a floating gimbal mechanism can
be included between force feedback mouse **800** and linkage **835** to provide additional degrees of
freedom to force feedback mouse **800**. Optionally, additional transducers can be also added to
electronic interface **810** in provided or additional degrees of freedom of force feedback mouse
**800**. In an alternate embodiment, the mechanism can be used for a 3-D interface device that
allows a user to move a user object in three dimensions rather than the 2-D planar workspace
disclosed. For example, in one embodiment, the entire mechanism can be made to rotate about
a grounded axis, such as axis H extending through the actuators **910**. For example, members
(not shown) rigidly coupled to the actuators **910** or to base **845** can extend in both directions
along axis H and be rotary coupled to a grounded surface at points H1 and H2. This provides a
third (rotary) degree of freedom about axis H. A motor can be grounded to the surface near
point H1 or H2 and can drive the mechanism about axis H, and a sensor, such as a rotary
encoder, can sense motion in this third degree of freedom. One reason for providing axis H
through the magnet assemblies is to reduce the inertia and weight contributed to motion about

axis H by the magnet assemblies. Axis H can be provided in other positions in other embodiments. In such an embodiment, the user object 130 can be a stylus, grip, or other user object. A third linear degree of freedom to mechanism can be provided in alternate embodiments. One embodiment of a planar linkage providing three degrees of freedom is

5      disclosed in co-pending patent application serial no. 08/736,161 filed 10/25/96 and hereby incorporated by reference herein in its entirety.

Figure 17C is a perspective view of the grounded pad 820 and electronic interface 810 of the mouse system, where the force feedback mouse 800 has been detached from

10     the mechanical linkage 835. As shown, pad 820 preferably has a height h and may be hollow to allow the mechanical linkage 835 to be positioned underneath the top surface of the pad 820. The bearing 895 may be arranged to extend through a guide opening 925 in the pad 820. An attachment plate 900 can be coupled to the bearing 895 or rotatably coupled to a member of linkage 835 to provide a point for attaching the force feedback mouse 800 to the linkage 835. in

15     one version, the force feedback mouse 800 is releasably coupled to attachment plate 900. In the described embodiment, the opening 925 provides the limits to the workspace of the force feedback mouse 800. Bearing 895 and plate 900 protrude through opening 925 such that a rounded portion of plate 900 (provided under the flat plate portion), when moved in any degree of freedom of the force feedback mouse 800, eventually impacts a side of opening 925. The

20     four sides to the opening 925 thus provide limits to the workspace of the force feedback mouse 800 in the provided planar degrees of freedom, i.e., a stop mechanism is provided that limits the movement of the force feedback mouse 800 as defined by the size of opening 925. Opening 925 can be made any size desired. For example, in the described embodiment, opening 925 has relatively small dimensions, such as approximately 1 3/8" by 1 1/8". The size of the opening

25     925 is larger than the workspace of the mouse due to the size or radius of the rounded portion; thus, with the described opening size, a workspace of about 1" by 3/4" is obtained for the force feedback mouse 800 (which is considered at the center of bearing 895 at axis D). This is typically adequate workspace for the user to move the mouse and control a graphical object such as a graphical image 115 on a display screen 155. In addition, this size workspace has an

30     aspect ratio of 4:3, which is about the aspect ratio of a standard computer monitor, television, or other display screen. An aperture 930 can also be provided to route wires or cables from buttons, for example, on the mouse to the electronic interface 810. Alternatively, an inductive coil can be included in force feedback mouse 800 to transmit a signal when a button is activated, where the signal is received by another inductive coil in pad 820 which detects the

activation of buttons, the operation of such coils being well known to those skilled in the art. Other wireless devices can also be used.

5 The top surface of grounded pad **820** may be a smooth material, such as a smooth slick plastic, to allow contact with portions of force feedback mouse **800**. Such contact provides support for force feedback mouse **800** when the mouse is moved in its planar workspace and allows the mouse to slide on the pad **820** with little friction. Since the linkage **835**, when extended, is cantilevered at a large moment arm, a small force at the mouse end of the linkage can create a large torque that stresses the mounting or coupling **880** at axis A, which 10 may use the mounting or coupling to bend. Pad **820** thus balances the cantilever load by providing support to any pressure or force from the user in the z-direction on force feedback mouse **800** toward the ground surface **825**.

Figure 18 is a block diagram illustrating a version of the haptic interface **140** comprising an electronic interface **810** and a mechanical interface **830** usable with the version 15 of the invention shown in Figures 10, and 11a-11c. The simulation system **100** includes a computer **150** and the haptic interface **140**. The computer **150** may include a host microprocessor **940**, random access memory (RAM) **945**, read-only memory (ROM) **950**, input/output (I/O) electronics **955**, a clock **960**, a display device **155**, and an audio output device 20 **965**. Host microprocessor **940** can include a variety of available microprocessors from Intel, AMD, Motorola, or other manufacturers. Host microprocessor **940** can be single microprocessor chip, or can include multiple primary and/or co-processors. Host microprocessor **940** preferably retrieves and stores instructions and other necessary data from RAM **945** and ROM **950** as is well known to those skilled in the art. In the described 25 embodiment, the computer **150** can receive sensor data or a sensor signal via a bus **205**. Host microprocessor **940** can receive data from bus **205** using I/O electronics **955**, and can use I/O electronics to control other peripheral devices. The computer **150** can also output commands to haptic interface device **140** via bus **205** to cause force feedback for the simulation system **100**.

30 Clock **960** is a standard clock crystal or equivalent component used by the computer **150** to provide timing to electrical signals used by host microprocessor **940** and other components of the computer **150**. Clock **960** is accessed by the computer **150** in the control process of the present invention to provide timing information that may be necessary in determining force or position, e.g., calculating a velocity or acceleration from position values.

Display device **155** is similar to that described above. Audio output device **965**, such as speakers, can be coupled to host microprocessor **940** via amplifiers, filters, and other circuitry well known to those skilled in the art. Host processor **940** outputs signals to speakers

5      **965** to provide sound output to the user when an "audio event" occurs during the implementation of the host application program. Other types of peripherals can also be coupled to host processor **940**, such as storage devices (hard disk drive, CD ROM drive, floppy disk drive, etc.), printers, and other input and output devices.

10     Haptic interface **140** includes an electronic interface **810** and a mechanical interface **830** (which each may include both electronic and mechanical components). The electronic interface **810** is coupled to the computer **150** by a bi-directional bus **205**. The bi-directional bus **205** sends signals in either direction between the computer **150** and the interface device **140**. Bus **205** can be a serial interface bus, as discussed above. A USB may serve as the

15     serial interface bus to also source power to drive actuators **910** and other devices. Since each device that accesses the USB is assigned a unique USB address by the computer **150**, this allows multiple devices to share the same bus. In addition, the USB standard includes timing data that is encoded along with differential data.

20     The electronic interface **810** includes a local microprocessor **970**, local clock **975**, local memory **980**, sensor interface **985**, and actuator interface **990**. Electronic interface **810** may also include additional electronic components for communicating via standard protocols on bus **205**. In various embodiments, electronic interface **810** can be included in mechanical interface **830**, in the computer **150**, or in its own separate housing. Different

25     components of electronic interface **810** can be included in interface **830** or the computer **150** if desired.

Local microprocessor **970** may be coupled to bus **205** and may be closely linked to mechanical interface **830** to allow quick communication with other components of the

30     interface device. Processor **970** is considered "local" to haptic interface **140**, where "local" herein refers to processor **970** being a separate processor, such as a microprocessor, from a processor **940** in the computer **150**. "Local" may also refer to processor **970** being dedicated to force feedback and sensor I/O of the haptic interface **140**, and being closely coupled to sensors and actuators of the mechanical interface **830**, such as within the housing of or in a housing

coupled closely to interface **830**. Microprocessor **970** can be provided with software instructions to wait for commands or requests from the computer **150**, parse/decode the command or request, and handle/control input and output signals according to the command or request. In addition, processor **970** may operate independently of the computer **150** by reading

5   sensor signals and calculating appropriate forces from those sensor signals, time signals, and force processes selected in accordance with a host command, and output appropriate control signals to the actuators. Suitable microprocessors for use as local microprocessor **970** include the MC68HC711E9 by Motorola and the PIC16C74 by Microchip, for example. Microprocessor **970** can include one microprocessor chip, or multiple processors and/or co-

10  processor chips. In other embodiments, microprocessor **970** can include digital signal processor (DSP) functionality.

For example, in one host-controlled embodiment that utilizes a local microprocessor **970**, the computer **150** can provide low-level force commands over bus **205**,

15  which microprocessor **970** directly transmits to the actuators **910**. In a different local control embodiment, the computer **150** provides high level supervisory commands to microprocessor **970** over bus **205**, and microprocessor **970** manages low level force control loops to sensors and actuators in accordance with the high level commands and independently of the computer **150**. In the local control embodiment, the microprocessor **970** can process inputted sensor signals to

20  determine appropriate output actuator signals by following the instructions of a "force process" that may be stored in local memory and includes calculation instructions, formulas, force magnitudes, or other data. The force process can command distinct force sensations, such as vibrations, textures, jolts, or kinesthetic forces simulating interactions between displayed objects in the graphical environment **110**. An "enclosure" host command can also be provided, which

25  causes the microprocessor **970** to define a box-like enclosure in a graphical environment **110**, where the enclosure has sides characterized by wall and texture forces, as described in U.S. Patent 6,100,874 which is incorporated herein by reference in its entirety. The computer **150** can send the local processor **970** a spatial layout of objects, such as a graphical object **120** in the graphical environment **110** so that the microprocessor **970** has a mapping of locations of

30  graphical objects like enclosures and can determine interactions with the graphical image **115** locally. Force feedback used in graphical environments is described in greater detail in U.S. Patents 5,629,594 and 5,825,308, both of which are incorporated by reference herein in their entireties.

Sensor signals used by microprocessor **970** are also reported to the computer **150**, which updates a host application program and outputs force control signals as appropriate. For example, if the user moves force feedback mouse **800**, the computer **150** receives position and/or other signals indicating this movement or manipulation of the user object **130** and can

5 move a displayed graphical image **115** in response. In an alternate embodiment, no local microprocessor is included in the haptic interface **140**, and the computer **150** directly controls and processes all signals to and from the electronic interface **810** and mechanical interface **830**.

A local clock **975** can be coupled to the microprocessor **970** to provide timing

10 data, similar to system clock **960** of the computer **150**; the timing data might be required, for example, to compute forces output by actuators **910** (e.g., forces dependent on calculated velocities or other time dependent factors). In alternate embodiments using the USB communication interface, timing data for microprocessor **970** can be retrieved from the USB interface. Local memory **980**, such as RAM and/or ROM, may be coupled to microprocessor

15 **970** in to store instructions for microprocessor **970** and store temporary and other data. Microprocessor **970** may also store calibration parameters in a local memory **980** such as an EEPROM. As described above, link or member lengths or manufacturing variations and/or variations in coil winding or magnet strength can be stored. If analog sensors are used, adjustments to compensate for sensor variations can be included, e.g. implemented as a look up

20 table for sensor variation over the user object workspace. Memory **980** may be used to store the state of the force feedback device, including a reference position, current control mode or configuration, etc.

Sensor interface **985** may optionally be included in electronic interface **810** to

25 convert sensor signals to signals that can be interpreted by the microprocessor **970** and/or the computer 150. For example, sensor interface **985** can receive signals from a digital sensor such as an encoder and convert the signals into a digital binary number representing the position of a member or component of mechanical apparatus **830**. An analog to digital converter (ADC) in sensor interface **985** can convert a received analog signal to a digital signal for microprocessor

30 **970** and/or the computer **150**. Such circuits, or equivalent circuits, are well known to those skilled in the art. Alternately, microprocessor **970** can perform these interface functions without the need for a separate sensor interface **985**. Alternatively, sensor signals from the sensors **905** can be provided directly to the computer **150**, bypassing microprocessor **970** and sensor interface **985**. Other types of interface circuitry can also be used.

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Actuator interface **990** can be optionally connected between the actuators **910** and microprocessor **970**. Actuator interface **990** converts signals from microprocessor **970** into signals appropriate to drive the actuators. Actuator interface **990** can include power amplifiers,

5     switches, digital to analog controllers (DACs), and other components. Such interfaces are well known to those skilled in the art. In alternate embodiments, actuator interface **970** circuitry can be provided within microprocessor **970** or in the actuators **910**.

In the described embodiment, power is supplied to the actuators **910** and any

10    other components (as required) by the USB. Since the electromagnetic actuators of the described embodiment have a limited physical range and need only output, for example, about 3 ounces of force to create realistic force sensations on the user, very little power is needed. A large power supply thus need not be included in interface system or as an external power adapter. For example, one way to draw additional power from the USB is to the  haptic

15    interface **140** to appear as more than one peripheral to the computer **150**; for example, each provided degree of freedom of force feedback mouse **800** can be configured as a different peripheral and receive its own allocation of power. Alternatively, power from the USB can be stored and regulated and thus used when needed to drive actuators **910**. For example, power can be stored over time and then immediately dissipated to provide a jolt force to the user object

20    **130**. A battery or a capacitor circuit, for example, can store energy and discharge or dissipate the energy when power is required by the system and/or when enough power has been stored. Alternatively, a power supply **995** can optionally be coupled to actuator interface **990** and/or actuators **910** to provide electrical power. Power supply **995** can be included within the housing of the haptic interface device **140**, or can be provided as a separate component, for example,

25    connected by an electrical power cord. The power storage embodiment described above, using a battery or capacitor circuit, can also be used in non-USB embodiments to allow a smaller power supply **995** to be used.

Mechanical interface **830** is coupled to the electronic interface **810** and may

30    include sensors **905**, actuators **910**, and linkage **835**. These components are described in detail above. Sensors **905** sense the position, motion, and/or other characteristics of force feedback mouse **800** along one or more degrees of freedom and provide signals to microprocessor **970** including information representative of those characteristics. Typically, a sensor **905** is provided for each degree of freedom along which force feedback mouse **800** can be moved, or,

a single compound sensor can be used for multiple degrees of freedom. Example of sensors suitable for embodiments described herein are optical encoders, as described above. Linear optical encoders may similarly sense the change in position of force feedback mouse **800** along a linear degree of freedom. Alternatively, analog sensors such as potentiometers can be used. It

5  is also possible to use non-contact sensors at different positions relative to mechanical interface **830**, such as Hall effect magnetic sensors for detecting magnetic fields from objects, or an optical sensor such as a lateral effect photo diode having an emitter/detector pair. In addition, velocity sensors (e.g., tachometers) for measuring velocity of force feedback mouse **800** and/or acceleration sensors (e.g., accelerometers) for measuring acceleration of force feedback mouse

10  **800** can be used. Furthermore, either relative or absolute sensors can be employed.

Actuators **910** transmit forces to force feedback mouse **800** in one or more directions along one or more degrees of freedom in response to signals output by microprocessor **970** and/or the computer **150**, i.e., they are "computer controlled." Typically, an

15  actuator **910** is provided for each degree of freedom along which forces are desired to be transmitted. Actuators **910** can include active actuators, such as linear current control motors, stepper motors, pneumatic/hydraulic active actuators, a torquer (motor with limited angular range), a voice coil actuator as described in the embodiments above, and/or other types of actuators that transmit a force to an object. Passive actuators can include magnetic particle

20  brakes, friction brakes, or pneumatic/hydraulic passive actuators, and generate a damping resistance or friction in a degree of motion. For example, an electrorheological fluid can be used in a passive damper, which is a fluid that has a viscosity that can be changed by an electric field. Likewise, a magnetorheological fluid can be used in a passive damper, which is a fluid that has a viscosity that can be changed by a magnetic field. These types of dampers can be

25  used instead of or in addition to other types of actuators in the mouse interface device. In yet other embodiments, passive damper elements can be provided on the bearings of interface **830** to remove energy from the system and intentionally increase the dynamic stability of the mechanical system. In addition, in voice coil embodiments, multiple wire coils can be provided, where some of the coils can be used to provide back EMF and damping forces. In

30  some embodiments, all or some of sensors **905** and actuators **910** can be included together as a sensor/actuator pair transducer.

The mechanism **835** may be the five-member linkage **835** described above, but can also be one of several types of mechanisms. Force feedback mouse **800** can alternatively be

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a puck, joystick, or other device or article coupled to linkage **835**, as described above.

Other input devices **1000** can optionally be included in system **100** and send input signals to microprocessor **970** and/or the computer **150**. Such input devices can include buttons, such as buttons on force feedback mouse **800**, used to supplement the input from the user to a simulation, GUI, game, etc, as will be discussed. Also, dials, switches, voice recognition hardware (with software implemented by computer **150**), or other input mechanisms can be used.

Safety or "deadman" switch **1005** may be included in haptic interface device **140** to provide a mechanism to allow a user to override and deactivate actuators **910**, or require a user to activate actuators **910**, for safety reasons, as discussed above.

In one version of the invention, a mouse **600**, which may be either a tactile mouse **250** or a force feedback mouse **800**, is used to control the display of a graphical hand **170**. Movement of the mouse **600** controls the positioning of the graphical hand **170** in the graphical environment **110**. For example, in one version, the two dimensional position of the mouse **600** directly controls the two-dimensional displayed position of the graphical hand **170**. In more complex version, the mouse **600** may be positionable in three dimensions and/or may to rotatable about one or more axes to control the three dimensional position and/or the orientation of the graphical hand **170**, as will be described.

In one version, one or more of the buttons **620** may be used to control the shape of the graphical hand **115**. Accordingly, when a button is depressed, the display of the shape of the graphical hand **170** may change. For example, a binary button, i.e. a button that is either "on" or "off" may be provided. When depressed, or when in the "on" condition, the graphical hand may be displayed in a grasping condition. In another version, a sensor, such as an analog sensor, is positioned to detect the amount of depression of the button **620** and the displayed graphical hand **170** shows the variable amount of grasping in response to the depression. For example, as shown in Figure 19A, a sliding member **1050** may be connected to the interior of a button, such as button **620a**, which is hingedly connected to the housing of the mouse **600**. Much of the interior of the mouse **600** is not shown for clarity. Alternatively, the button may be slidingly connected to the mouse **600** housing. The sliding member **1050** slides within a sensor **1060**. The sensor **1060** may comprise, for example, a potentiometer, an encoder, LVDT, or

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similar device. A signal from the sensor **1060** is transmitted to the computer **150** which uses the signal to control the display of the graphical hand **170**. In one version, the graphical hand may comprise three displayed positions. The first position is an open hand and is displayed when the button **620a** has not been depressed a predetermined amount. When the button **620a** reaches the

5     predetermined amount, the graphical hand **170** is shown in a semi-closed position. When the button **620a** is further depressed to a second predetermined position, a closed hand is shown. In more advanced versions, the display of the grasping action can be directly related to the amount of depression of the button **620a**.

10    An actuator **1070** may be provided, as shown schematically in Figure 19A, to provide a haptic sensation to the button **630a**. For example, a haptic sensation may be provided to simulate a resistive grasping force, indicating to the user that an object is being grasped. Alternatively or additionally, tactile sensations such as vibrations may be output to the button to provide various indications to the user. Figure 19B shows another version of a button sensor

15    **1060** and a button actuator **1070** embodied in a motor/encoder pair. The button actuator **1070** comprises a motor having a rotatable shaft **1065** connected to a toothed wheel **1090**. The teeth on the toothed wheel engaging teeth **1080** on an extension member **1085** to allow the motor to drive the button **630a**, optionally in either direction. An encoder or the like is positioned to detect rotation of the shaft and to correlate the detected rotation to a position of the button **630a**.

20    Another version of a button actuator **1070** is shown in Figure 19C. In this version, the button actuator **1070** comprises a deformable leaf spring **110** that may be actuated by pulling on tendon **250** in the direction of arrow **1105**, as discussed above in connection with Figures 4A-4C and 5A-5B. In addition, a motor or the like may be positioned within the mouse **600** or exterior to the mouse **600** and may comprise a position detector, such as an encoder, that may be used to

25    detect a position of the button **630a** since the linear position of the tendon **250** is related to the depressed position of the button **630a**.

In another version, the depression of a button **620** may result in the bending of a finger on the graphical hand **170**. In one version, such as the version shown in Figure 12, a

30    button depression sensor is provided for all five fingers, each finger being able to independently control the bending of corresponding fingers on the graphical hand **170**. Accordingly, a user may depress button **620a**, for example, and the graphical hand's index finger may be displayed as bending. Optionally, each button **630** may also be provided with an actuator to provide a haptic sensation to each of the fingers. In an advanced version, each actuator is independently

controllable to provide independent haptic sensations to each of the fingers. These sensations may also be provided in addition to the haptic sensations provided to the palm through the housing of the mouse and in addition to any kinesthetic force feedback that is provided to the user.

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Another version of a finger sensing mouse is shown in Figures 20A and 20B. In this version, a finger receiving extension **1110** is attached to the button **620a**. The finger receiving extension **1110** includes a ring **1115** and a link **1120** connecting the ring **1115** to the button **620a**, as can be seen in Figure 20B which shows the view from the perspective of B-B in

10    Figure 20A. With this version, the user inserts his or her finger into the ring **1115**. Accordingly, the user is able to manipulate the button **620a** in both directions, rather than just depression of the button **620a**. Accordingly, the user can actively open a closed graphical hand **170**. Optionally, an actuator **1070**, such as the actuator shown in Figure 19B, may be provided to apply forces to the finger in both directions. Alternatively, the button may be removed and

15    replaced with a linear or curved rod **1125** that extends through the housing of the mouse **600** and is engaged by a sensor **1060** and/or an actuator **1070**, as shown in Figure 21. In another version, as shown in Figure 22, the finger receiving extension **110** may comprise a ring **1115** mounted to an articulated linkage **1130** which is mounted on the mouse **600**, for example by being mounted on the housing of the mouse **600**. The linkage **1130** may include any number of

20    revolute joints **1135**, such as three as shown. An encoder or other type sensor may detect the angular position of the revolute joints **1135** to determine the position of the ring **115** and thereby determine the position of the finger of the user. In another version, each revolute joint **1115** is provided with a rotary actuator, such as a motor, to provide force feedback to the finger. Alternatively to the configuration shown in Figure 22, a five-bar linkage, with the housing of

25    the mouse **600** being one of the bars, may be used to provide position sensing and actuation of the finger. In one version, a revolute joint **1140** is provided to detect rotation of the ring **1115** about axes that lie in the plane of the cross-section of Figure 22. Additionally or alternatively, a linkage may be provided that is allows the ring **1115** to move perpendicularly to the plane of the cross-section of Figure 22, and the ring **115** may be sensed and/or forced in that movement.

30    This version allows for the detection of spreading of the fingers and crossing of the fingers. The finger receiving extensions of Figures 20 through 22 may be provided any number of fingers of the user, including all five fingers of the hand of the user. In another version, the linkage **1130** may be connected to a grounded member instead of to the mouse **600**. In another version, the linkage **1130** may be connected to the user, for example by being connected to the wrist or hand

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of the user as described in U.S. Patent 6,110,130 which is incorporated herein by reference in its entirety.

5   Another version of a finger sensing button **620a** is shown in Figures 23A and 23B. This version comprises an articulated button **1150**. The articulated button **1150** comprises a first portion **1160** is articulatable relative to a second button portion **1170**. The first button portion **1160** may be adapted to contact a first finger portion **1165** and the second button portion **1170** may be adapted to contact a second finger portion **1170**. In this way, the position of the finger tip may be detected and the relative positions of the first and second portions of the

10  fingers can be detected. A more complex version includes three articulated button portions. Optionally one or more actuators may be provided to apply a force to the finger through one or more of the portions.

Figure 24 shows a mouse **600**, capable of sensed movement in three dimensions. Movement in two dimensions may be provided by a mechanism a mechanical interface **830**

15  similar to that shown in Figure 17. However, instead of being connected directly to the mouse **600**, the mechanical interface **830** is connected to a z-axis translation member **1200**. The z-axis translation member **1200** in the version shown comprises telescoping rods **1210,1220**. The top rod **1210** is connected to the mouse **600**. Thus, the mouse **600** may be moved in three dimensions. A linear potentiometer or encoder or the like may be positioned to detect the

20  displacement of the telescoping rods **1210, 1220** in order to generate a signal that may be used by the computer to control the graphical image **115** in a third dimension. Also, a linear motor, or the like, may be provided to apply force feedback to the mouse **600** in a third linear dimension. In addition, rotation of the mouse **600** about the z-axis can be sensed by measuring

25  the rotation between the telescoping rods **1210, 1220** and by non-rotatably connecting the base **1230** of the mouse **600** to the top rod **1210**. If desired, an articulation **1250** may be provided to allow the mouse **600** to rotate about the x axis, and an articulation **1260** may be provided to allow the mouse **600** to rotate about the y axis. These articulations may also include a rotation sensor to control the display of the graphical image **115** and/or a rotary actuator to provide force

30  feedback in these additional degrees of freedom. In one version, the mouse **600** is capable of up to six degrees of freedom of movement, is sensed in up to six degrees of freedom, is forced in up to six degrees of freedom, and includes from one to five finger sensing buttons **620**. Alternatively, a three dimensional linkage system such as those described in U.S. Patents 5,701,140 and 5,625,576, which are incorporated herein by reference in their entireties, may be

used. In these version, a mouse **600** with one or more finger sensing buttons **620** may be mounted on the linkage.

Graphical image controlling mouse alternatives are shown in Figures 25A through 25C. In the version of Figure 25A, an orientation ball **1300** is provided at the distal end of the mouse **600** instead of or in addition to the finger sensing buttons **620**. Figure 25B shows a frontal view of the mouse **600** of Figure 25A with a user grasping the orientation ball **1300** with his or her thumb and first two fingers. By rotating the orientation ball about the longitudinal axis of the mouse **600**, for example, the user can control the orientation of the graphical image **115** about an axis. A retainer **1310** may be rotatable so as to not interfere with the motion of the fingers. In another version, the orientation ball **1300** is rotatable about three orthogonal axes, in a manner similar to a track ball, to control the orientation of the graphical image **115** in about three orthogonal axes. Alternatively, as shown in Figure 25C, an additional orientation of the graphical image **115** can be controlled by rotating the mouse **600**. The rotation can be detected by providing two longitudinally spaced mouse balls **665, 665'**. By comparing the position signals from the two balls **665, 665'**, the orientation of the mouse **600** can be determined. This orientation can then be used by the computer **150** to update the display of the graphical image **115**, such as a graphical hand **170**, accordingly.

In one version of the invention, a networked connection may be provided, for example as described in U.S. Patent Application 09/153,781 filed on September 16, 1998, which is incorporated herein by reference in its entirety. In this version, a user may download an application program, such as a virtual reality simulation program, or a file of haptic sensations from a remote location. Also, a user may interact with a simulation running at a remote location. In another version, the haptic interface may be used as a master device to control a remote slave device. The slave device may be representative of the user's hand or fingers for example, and the user may control the slave to, for example, perform a procedure at a remote location. In an advanced version, the slave device may be equipped with sensors to detect conditions of the slave device, such as pressures or forces. The sensed conditions may then be used to provide haptic sensations to the user via the master device, the haptic sensations being related to the sensed conditions of the slave device.

While this invention has been described in terms of several preferred embodiments, it is contemplated that alterations, permutations and equivalents thereof will

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become apparent to those skilled in the art upon a reading of the specification and study of the drawings. For example, many different types of haptic sensations can be provided with the haptic interface of the present invention and many different types actuators and user objects can be used, including the use of two user objects to detect manipulation of both hand of a user. In addition, the haptic interface can be replaced by a non-haptic interface, for example, when the mapping of the graphical image is broken. Furthermore, certain terminology, such as terms like x, y, z, left, right, up, down, etc., has been used for the purposes of descriptive clarity, and not to limit the present invention. Therefore, the appended claims should not be limited to the description of the preferred versions contained herein and should include all such alterations, permutations, and equivalents as fall within the true spirit and scope of the present invention.